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Wind Shear/Turbulence Inputs to Flight Simulation and Systems Certification

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Langley Research Center
Hampton, Virginia
May 30–June 1, 1984

NASA

NASA Conference Publication 2474

Wind Shear/Turbulence Inputs to Flight Simulation and Systems Certification

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Proceedings of a workshop sponsored by the
National Aeronautics and Space Administration,
and held at Langley Research Center
Hampton, Virginia
May 30–June 1, 1984

NASA
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and Space Administration

Scientific and Technical
Information Office

1987

PREFACE

This Conference Publication contains the proceedings of a workshop on Wind Shear and Turbulence Inputs to Flight Simulation and Systems Certification held at the Langley Research Center, Hampton, Virginia, on May 30 - June 1, 1984. The purpose of the workshop was to provide a forum for industry, universities, and government to assess current status and likely future requirements for application of flight simulators to aviation safety concerns and system certification issues associated with wind shear and atmospheric turbulence. Approximately 60 industry, government, and university representatives participated in the workshop.

The conference organization provided participants the opportunity to highlight and disseminate major research findings in regard to the characterization of wind shear and turbulence hazards based on modeling efforts and quantitative results obtained from field measurement programs. Future research thrusts needed to maximally exploit flight simulators for aviation safety application involving wind shear and turbulence were identified.

The conference contained sessions on: Existing Wind Shear Data and Simulator Implementation Initiatives; Invited Papers Regarding Wind Shear and Turbulence Simulation Requirements; and Committee Working Session Reports. The published proceedings also include impromptu presentations and documentation of general discussion.

Use of trade names or names of manufacturers in this report does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

Roland L. Bowles
Langley Research Center

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OVERVIEW OF WIND SHEAR DATA
AND
SIMULATOR IMPLEMENTATION INITIATIVES

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CASE HISTORY OF FAA/SRI WIND SHEAR MODELS

Herbert Schlickenmaier
Aerospace Engineer
Federal Aviation Administration

INTRODUCTION

In order to understand the development of the FAA/SRI wind fields, it is important to understand the operating philosophy of the FAA's Wind Shear Program Office at the time.

The goal of the program office was to ensure an integrated solution to the wind shear problem that addressed three areas:

- Ground-based equipment and coordination
- Airborne systems and procedures
- Weather prediction

This triply-addressed goal was central to the development of the wind fields. Without sounding too obvious, your organization's philosophies and project goals will have a profound effect on your use of the JAWS data along with its associated form and complexity.

The primary user of the wind shear modeling during the FAA's program was airborne simulation. The project requirement was to use wind shear models that resulted from accidents so that effective procedures and/or equipment could be found for hazardous wind shear encounters (see Figure 1). Our data sources in 1975 and 1976 were basically of two varieties: typically those that were recreated from actual accidents; and, at the other extreme, what might be considered untried models from tower measurements, and models that were mathematically synthesized. In order to make use of what had been proven to be the most hazardous wind shears at the time, the program office opted for wind models which were recreated from actual accidents. As you might expect, our sources were limited for a number of reasons, the most important being that the aircraft involved in the accidents were ill-equipped to record wind information. The methods, therefore, to recover this data were fraught with peril.

For those of you who are familiar with aircraft winds reconstruction, please bear with me. Figure 2 shows a simple overview of a typical accident recreation. I have taken the simple case of a 4-channel flight data recorder that collects airspeed, heading, altitude, and normal acceleration versus time. I have called the first phase of this "Recreation." It is primarily concerned with the flight dynamics of the aircraft and results in a number of wind models that approximate the data recorded on the flight data recorder. The next phase is "Selection," if you will; it is primarily a result of matching the meteorological conditions with the wind data extracted from the recreation. After iteratively working between "Recreation" and "Selection", the final wind model will converge as the wind shear model. This wind shear model could then be transformed into a profile against either altitude, distance, or some other combination, such as time.

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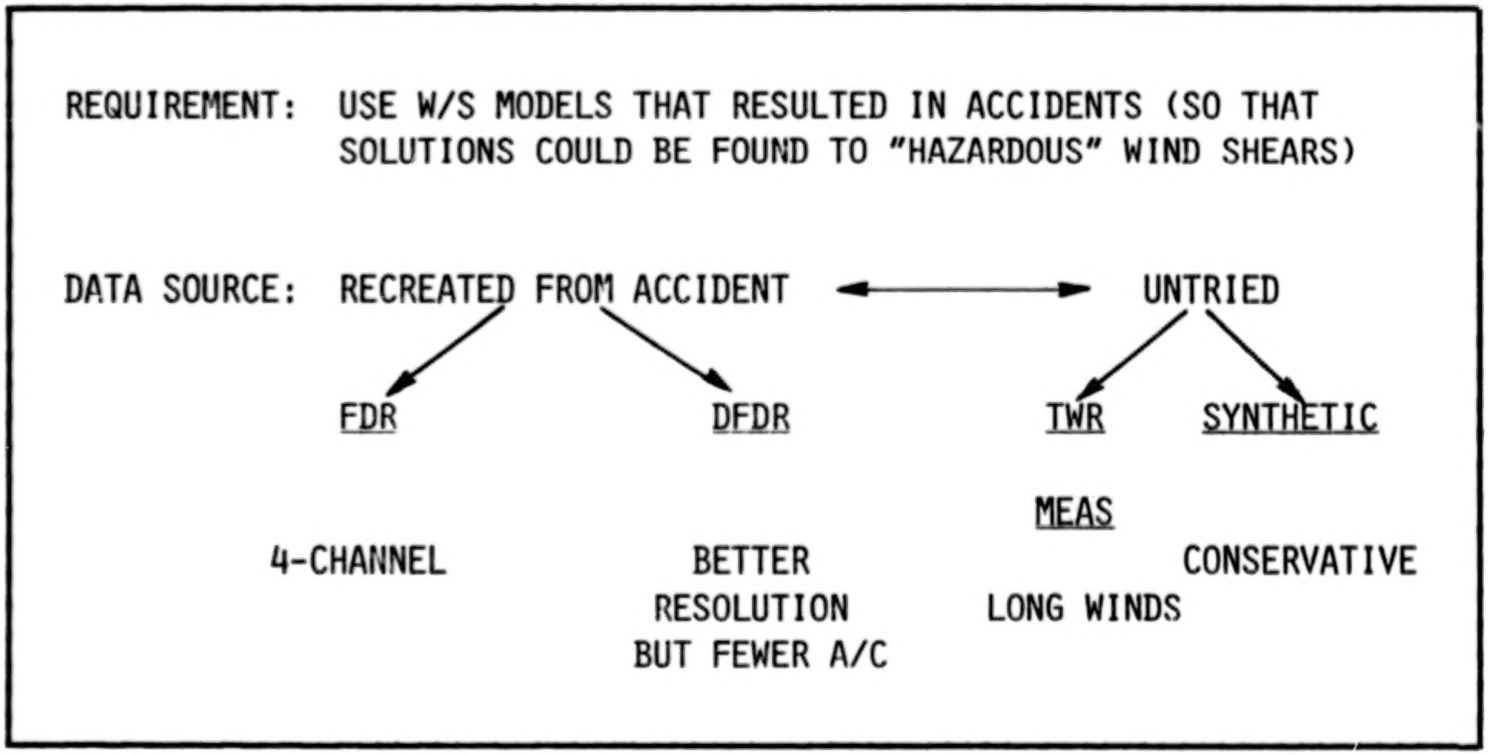

REQUIREMENT: USE W/S MODELS THAT RESULTED IN ACCIDENTS (SO THAT SOLUTIONS COULD BE FOUND TO "HAZARDOUS" WIND SHEARS)
DATA SOURCE: RECREATED FROM ACCIDENT
UNTRIED
FDR
DFDR
TWR
SYNTHETIC
MEAS
4-CHANNEL
BETTER RESOLUTION BUT FEWER A/C
LONG WINDS
CONSERVATIVE

Figure 1. Airborne Simulation

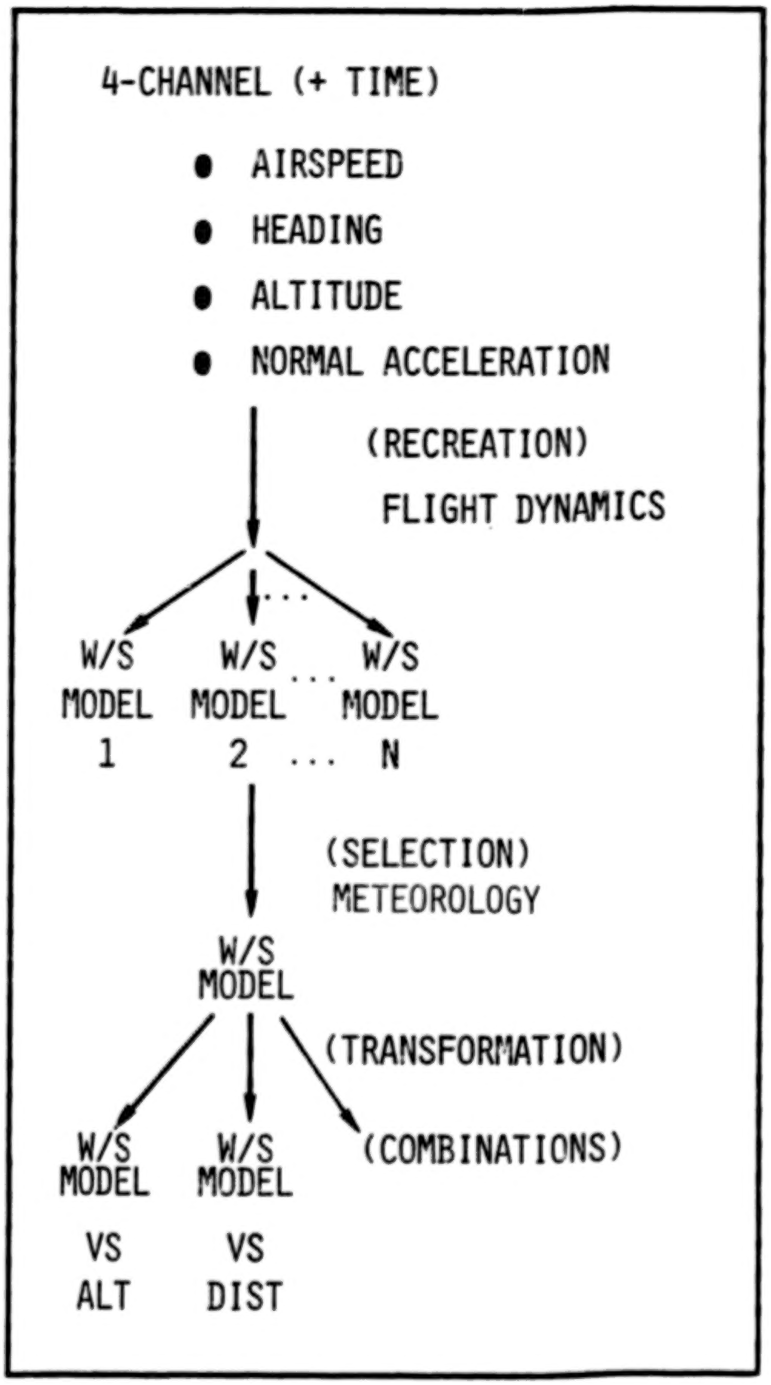

4-CHANNEL (+ TIME)
AIRSPEED
HEADING
ALTITUDE
NORMAL ACCELERATION
(RECREATION)
FLIGHT DYNAMICS
W/S MODEL 1
W/S MODEL 2
W/S MODEL N
(SELECTION)
METEOROLOGY
W/S MODEL
(TRANSFORMATION)
W/S MODEL VS ALT
W/S MODEL VS DIST
(COMBINATIONS)

Figure 2. Accident Wind Shear Recreation Overview

As outlined in Figure 3, a number of wind shear models were developed in this manner and were used in our Phase-I piloted simulations using a DC-10 aircraft model at McDonnell Douglas, Long Beach. The wind shear models were the Eastern 66 accident recreation at JFK, and the Iberian DC-10 at Boston Logan. As a baseline, we included a logarithmic wind speed profile also. We used a wind shear profile that consisted of winds versus altitude and we found that the pilots, unfortunately, could cancel the wind shear by leveling off. The pilots could actually improve their performance by performing a missed-approach climb-out. In essence, the wind models were only usable in the restricted flight scenario that we established for our Phase-I test; i.e., an ILS approach, 3° glide slope, and committed to land.

To evaluate anything more sophisticated, we had to revise the wind shear models (Figure 4) while maintaining the essence of the models used in the Phase-I test. In order to perform this expansion, our contractor, SRI International, pulled together a very formidable team of experts in meteorology, fluid dynamics, and simulator technology in order to produce a wind field. This field was a matrix that represented the longitudinal, lateral and vertical winds at various altitudes and distances.

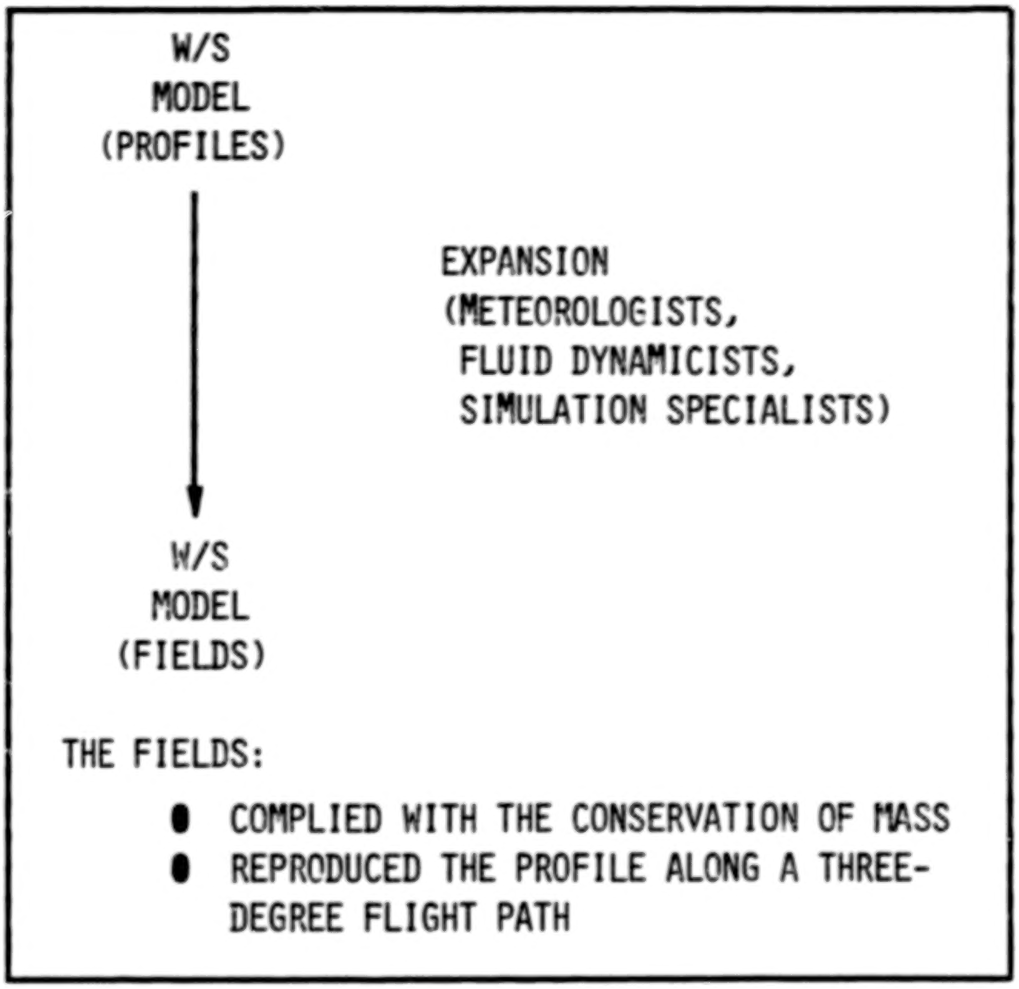
As I mentioned earlier, the goal of the FAA wind shear program office was to be an integrated triad of supporting solution. We used the wind fields to meet two elements of the triad (Figure 5), namely, the airborne systems and procedures investigations, and ground systems analysis. Our piloted flight simulations included the Phase II, III and IV DC-10 simulations at Long Beach, the NASA Ames 737 and 727 simulations, and support for an Air Force test at Altus with their C-5 simulation for the Military Airlift Command. We also attempted to support the surface wind measurement system (the research predecessor to what is now known as the Low-Level Wind Shear Alert System (LLWSAS)) by performing sensitivity analyses of some of the proposed sites. As you can see, the wind fields were also used to investigate wind shear warning system designs and low-cost ground speed sensors performance, and for parts of the head-up display program development in the research and development days.

As you might imagine, the wind fields were beginning to gain some popularity as an ad hoc standard, and they were provided to approximately 25 people in the U. S. (Figure 6). The documentation was limited and included an overview (along with usage and limitations) and a listing of the image of the wind field data, which was supplied on either magentic tape or punch cards. The Wind Shear Program Office was the focal point for the data. Because of the ad hoc nature of this distribution--I think this is crucial--there was little or no formal procedure for incorporating revisions and disseminating them to the users. (In defense of this statement, however, there was really no follow-up from any of the users to which we had shipped the data.) I find that is one of the crucial points in the use of the JAWS data. How do you disseminate it; how do you control it?

Finally, where does that leave us with the JAWS data? As you have heard, the JAWS data is rich. The olympic feats that were performed to extract first the FAA wind profiles, then the FAA/SRI wind fields, are almost trivialized in the light of the kind of wind shear information captured in the JAWS data; but in order for us to get you, the research users, good JAWS information as soon as possible, we need help in understanding your use of the data and the control for disseminating the data that you expect from us.

- W/S MODELS
    - JFK INTERNATIONAL AIRPORT
    - BOSTON LOGAN AIRPORT
    - WIND SPEED PROFILE
- WINDS VS ALTITUDE
- WIND MODEL FINDINGS:
    - PILOTS CANCEL W/S EFFECTS BY LEVELING OFF
    - PILOTS COULD IMPROVE PERFORMANCE BY CLIMBING OUT
- THE WIND MODELS WERE USABLE ONLY IN A RESTRICTED FLIGHT SCENARIO (ILS APPROACH AND COMMITTED TO LAND)

Figure 3. Phase-I Piloted Simulation Experience



W/S
MODEL
(PROFILES)

EXPANSION
(METEOROLOGISTS,
FLUID DYNAMICISTS,
SIMULATION SPECIALISTS)

W/S
MODEL
(FIELDS)

THE FIELDS:

- COMPLIED WITH THE CONSERVATION OF MASS
- REPRODUCED THE PROFILE ALONG A THREE-DEGREE FLIGHT PATH

Figure 4. Wind model revision

- PILOTED FLIGHT SIMULATIONS:
    - PHASE II, III, AND IV (DC-10)
    - NASA/ARC (B-737/727)
    - USAF (C-5A)
- GROUND SYSTEM ANALYSIS
    - SWIMS
- AIRBORNE SYSTEM ANALYSIS
    - WIND SHEAR WARNING
    - GROUNDSPEED SENSOR
    - HEAD-UP DISPLAY

Figure 5. FAA Use of the Wind Fields

- WIND FIELDS WERE PROVIDED TO 25 PEOPLE IN THE U. S.:
  - DOCUMENTATION
    - OVERVIEW AND USE
    - LISTING IMAGE
  - DATA
    - MAGNETIC TAPE
    - PUNCH CARDS
- FOCAL POINT
  - FAA WIND SHEAR PROGRAM OFFICE
- UPDATES/REVISIONS
  - NO FORMAL PROCEDURE FOR INCORPORATING AND DISSEMINATING TO USERS

Figure 6. Public Dissemination of the Wind Fields.

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HISTORY OF WIND SHEAR TURBULENCE MODELS

Lou Cusimano
Office of Flight Operations
Federal Aviation Administration

INTRODUCTION

The Office of Flight Operations, Flight Technical Programs Division, at the Federal Aviation Administration (FAA) Headquarters in Washington, DC, interfaces with industry, R&D communities and air carriers during the introduction of new types of equipment into operational services. This is a brief highlight of the need which FAA operations sees for new wind shear and turbulence data sets from the viewpoint of equipment certification and simulation.

Last November our office published Advisory Circular 120-41 (ref. 1) "Criteria for Operational Approval of Airborne Wind Shear Alerting and Flight Guidance Systems." In general, it lays out a method for air carriers to receive operational approval to use airborne wind shear devices in revenue services. Part of that methodology requires the use of some type of simulation of wind shear for the purpose of evaluating the effectiveness of a system.

In that document, we did not define any particular wind models for an applicant air carrier to use. Instead, we included the SRI data sets as an example of wind shear model simulation format as well as a challenge to the individual applicant to develop a model which would be effective for his particular situation. We also made a promise in that advisory circular to continue working toward the development of more specific wind shear models, and publish the same as soon as they were available.

Ultimately, we would like to provide a sample of acceptable wind shear models for the various aircraft performance characteristics commonly used in air carrier operations today; and, in that way, unburden the applicant to a certain extent in the approval process. After all, we are trying to encourage the use of these systems, not discourage their use.

In addition to airborne wind shear devices, we also work very closely with FAA's Directorate Certification Regions in the approval of other types of equipment requiring realistic turbulence and wind shear simulation models. An example of this is autoland systems, which are used in Category III operations and head-up displays, and also for low-visibility approaches. Of course, there are advisory circulars available which deal with those types of approvals; and, for real need for a continuing effort in developing realistic models which can be utilized for these efforts. Also, more research into the characterization of turbulence is needed, particularly very close to the ground, where it most effects the outcome of an approach.

Training aircrews to deal with wind shear, if they inadvertently find themselves in it, is very important to the air carrier operations staff. Of course, that training can best be carried out with realistic simulation models. It is my belief that NASA, NCAR, NOAA, and many of the other organizations have tremendous capability and a challenge from industry to move ahead in the development of these new models.

REFERENCE

1. Criteria for Operational Approval of Airborne Wind Shear Alerting and Flight Guidance Systems. Advisory Circular 120-41, Federal Aviation Administration, Nov. 1983.

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INTRODUCTION TO THE JAWS PROGRAM

John McCarthy
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The JAWS Project is the Joint Airport Weather Studies Project conceived in 1980 jointly between the National Center for Atmospheric Research and The University of Chicago. Funding has come primarily from NSF, FAA, NASA, and NOAA. The JAWS Project is a multi-agency program that, in a sense, is only loosely coordinated. The aspect of the simulation work has been coordinated through the ad hoc committee. Some of the members are listed in Figure 1: McCarthy and Wilson at NCAR; Fujita at The University of Chicago; Walt Frost, who has been heavily involved in the program since the early days through The University of Tennessee Space Institute and FWG Associates, Inc.; Dennis Camp with NASA Marshall Space Flight Center; a number of members at NOAA are directly involved in the program; The University of Wyoming; Alan Woodfield from the United Kingdom; and Lloyd Stevenson from DOT's Transportation Systems Center. Industry has also been involved. For example, United Airlines, through their Flight Training Academy at Denver, has been involved in simulation work. Boeing and Douglas have been involved. It is a rather loosely knit group of people trying to get the job done. We are well coordinated in some ways and in some ways, not so well coordinated.

The objectives of the program have been threefold: 1) Basic scientific characterization, primarily of the microbursts and the statistics of microburst occurrence: we are putting a great deal of effort into understanding the mechanisms which cause microbursts; 2) Detection and warning: we have looked hard at the Low-Level Wind Shear Alert System (LLWSAS) in terms of how well it operated in our program and how it needs to be improved; 3) Doppler radar and airborne systems: we are not directly involved in airborne systems at NCAR, so we are looking at that less hard than at the ground-based Doppler. In aircraft performance, we are concentrating a lot of effort on the very serious issue of pilot awareness. Pilots, unfortunately, are just not terribly aware. We are disseminating information on the program in terms of awareness and certain aspects of training issues, as well as the issue of simulation which is just a piece of the puzzle. Our primary goal is to provide the most realistic three- and four-dimensional microburst data suitable for simulation for government and industry. What government and industry choose to do with these data sets is undetermined. There are probably as many interests in doing something with these data sets as there are people. There are many directions in which you can go. Our objective has been this: given that the SRI profiles are limited, as Herb Schlickermaier has described (ref. 1), can we do better? The answer is absolutely yes. It is also our objective, along with that of the ad hoc committee, to disseminate the best data sets that we can.

The impetus for the program was Fujita's analysis of Eastern 66 and Continental's analysis of Continental 426. In putting the JAWS Project together, we felt that we did not properly understand the convective microburst. I think everybody here knows the implication of a microburst, that it is not good on approach or takeoff if you encounter one. We chose Stapleton because Continental 426 crashed there on takeoff. We had reason to believe there were lots of microbursts there. During JAWS, we had

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UNIVERSITY OF CHICAGO (Fujita)

FWG ASSOCIATES/UTSI (Frost)

NASA MARSHALL SPACE FLIGHT CENTER (Camp)

NOAA:
- PROFS (Alberty)
- WPL (Bedard)
- WRP (Caracena)

UNIVERSITY OF WYOMING (Rodi)

UNITED KINGDOM RAE (Woodfield)

TRANSPORTATION SYSTEMS CENTER-DOT (Stevenson)

Figure 1. Key members in JAWS Project.

far more microbursts there than we had ever dreamed could possibly occur over an airport, thus justifying our hopes.

The focus of the program was multiple Doppler radar, as reflected in Kim Elmore's report (ref. 2). We had three Doppler radars located in and around Stapleton. We has 27 surface wind measurement systems to try to get as much high-resolution information as we could. We used aircraft and we had our own wind-measuring systems distributed around the airport in addition to the LLWSAS, which was recorded for the JAWS Project. One of the three Doppler radars used was located across from the terminal building. Figure 2 shows a hook echo from an Oklahoma severe thunderstorm for a radar located nearby. We are looking at conventional intensity for a Doppler radar. If we look at it on the Doppler channel, it shows the location of a mesocyclone with winds moving toward and away from the radar; and the Doppler very nicely shows the location of a circulation which is about 15 or 20 km across. Near the center of the circulation is an actual tornado. Doppler is primarily a wind-detecting system and is the basis for developing the NEXRAD program which is the new development of Doppler throughout the United States. Figure 3 shows another sequence to give you another notion of the use of Doppler radar. The figure shows a line of heavy thunderstorms near Sacramento, California, which have two thin spots, however. PSA chose to go through the thin spot which, in fact, appeared as a hole on his X-band radar. The Doppler channel, on the other hand, shows an intense shear southeast in the other. A shear detector on the radar, where the maximum color change shows the maximum shear, indicates the spot he chose to go through was a maximum. So, what appeared to be an actual hole on his airborne radar was the location of a tornado cyclone. The tornado hit the ground ten minutes after he went through. He did get through, by the way, but just barely. At the same time he went through, there was a tornado on the ground just outside Sacramento. So, those are the kinds of things that Doppler can do.

Figure 4 is a Doppler of a microburst, taken from reference 3. The microburst has hit the ground, and spread out in all directions; but we see only the flow toward the radar or away from the radar. The distance between is about 2-1/2 km and the velocity difference shown is about 70 kt across about 8,000 ft. That is at the ground or close to the ground.

Figure 5 shows a direct hit of a microburst on the NOAA P-3 airborne Doppler system, which flew right through the middle of the generation region at 20,000 ft. The system looked straight down, and captured the downdraft of a microburst right in the center.

I have been using the next two figures in pilot-awareness talks. Pilots know not to go down the road, but to go either right or left in the kind of situation shown in Figure 6. This is nothing new; and everybody knows to dig a hole with your bare hands when you see something like this coming. Figure 7 is Fujita's famous picture at Stapleton, with high-based virga, no thunderstorm, and wind shear at the surface in a microburst...a very benign appearing situation which is quite severe and very similar to the appearance during the Continental 426 accident at Denver. Figure 8 is a picture of a high-based virga coming down and a dust cloud on the ground. It is a very benign appearing picture, but probably conceals very dangerous wind shear.

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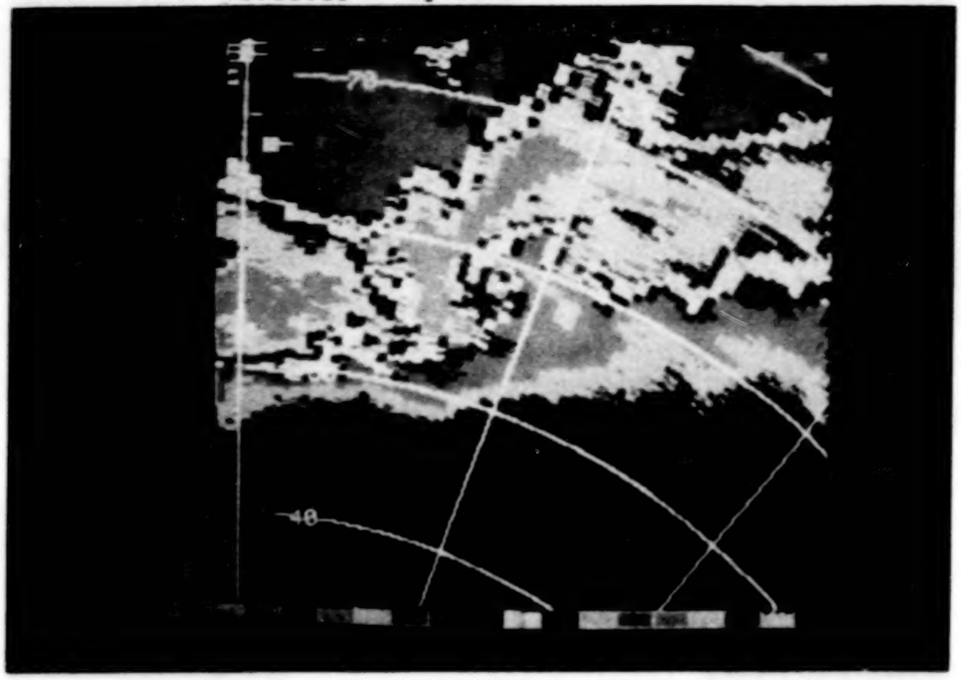

16:30:30 2 May 1979

Figure 2a. Hook echo seen in radar reflectivity for an Oklahoma tornado storm.

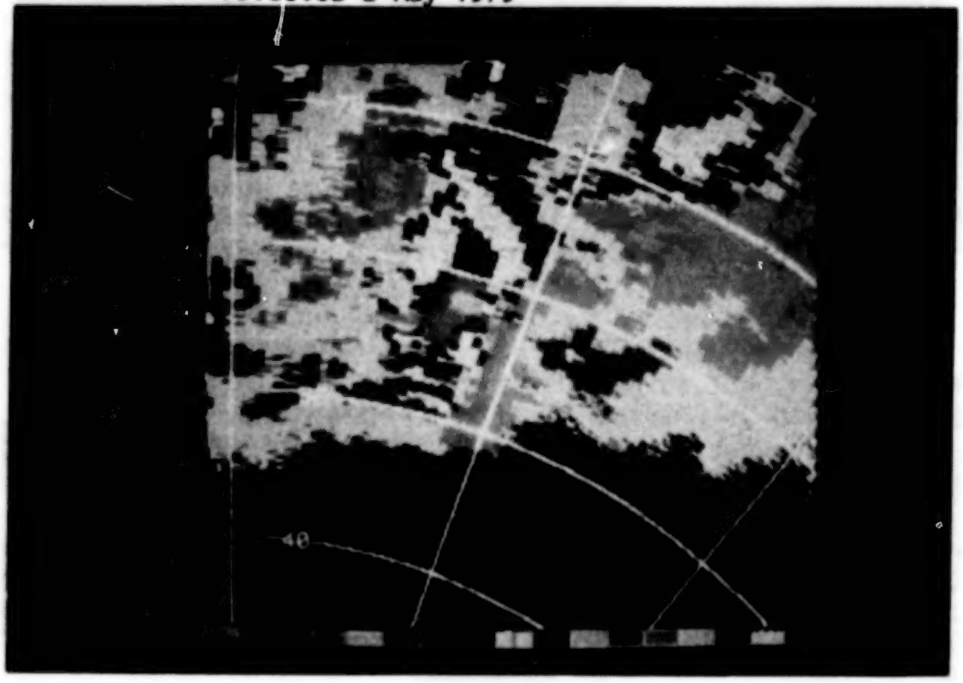

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Figure 2b. Associated Doppler velocity picture of same, showing meso- and tornado-cyclone.

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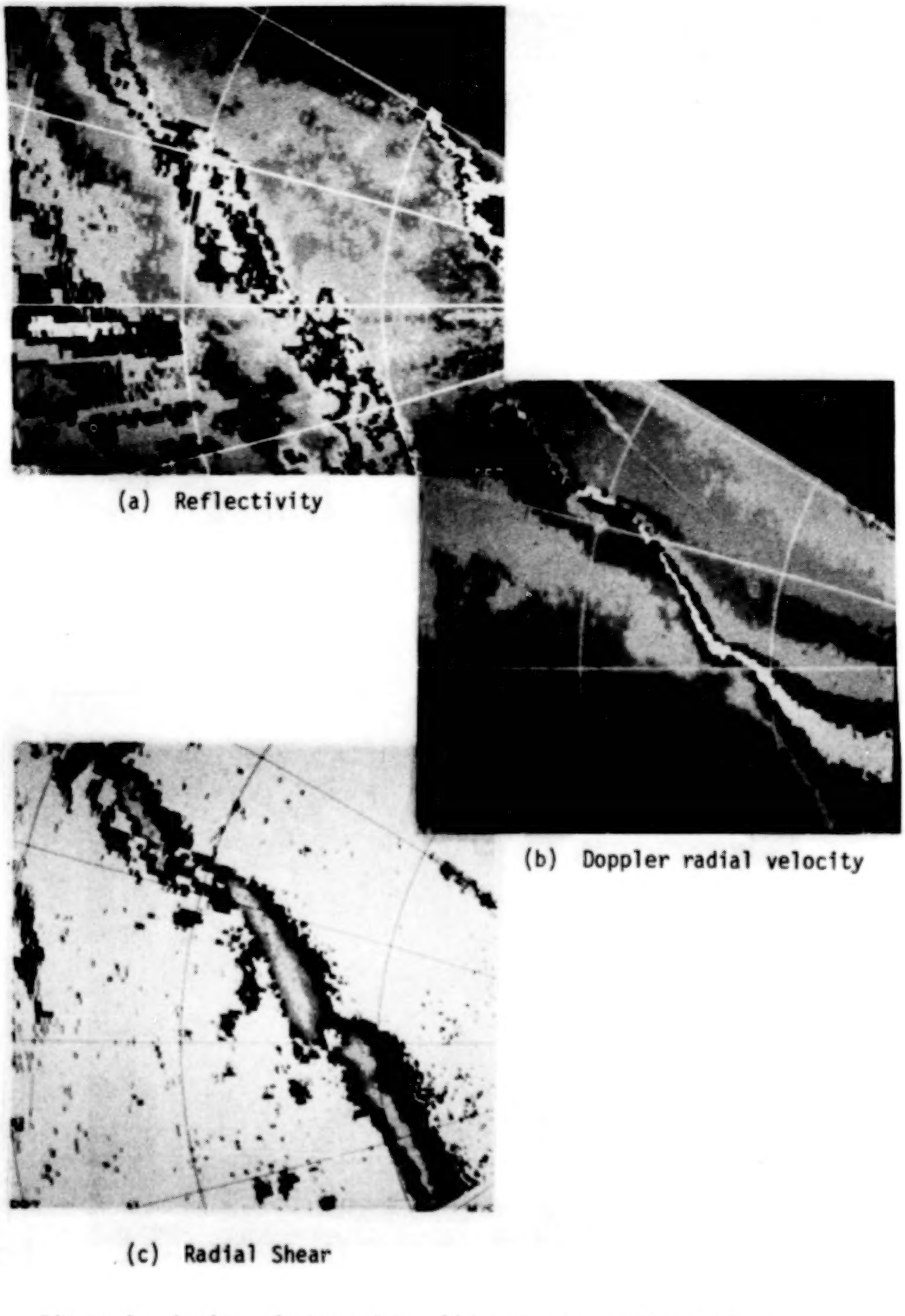

(a) Reflectivity

(b) Doppler radial velocity

(c) Radial Shear

Figure 3. Series of three data slides showing a line of heavy thunderstorms near Sacramento, California, which contains severe shear.

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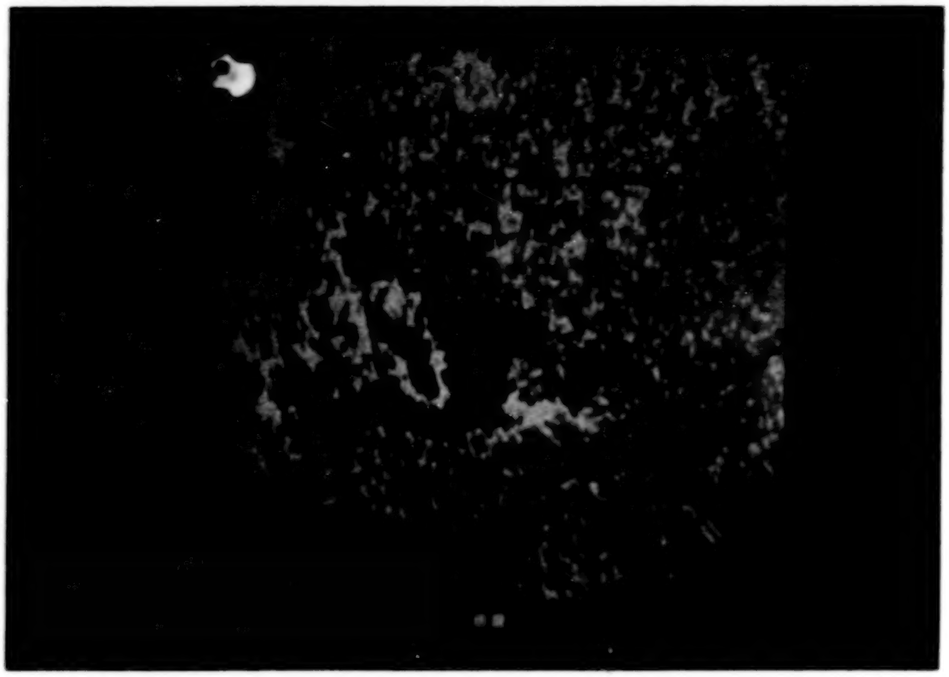

Figure 4. Doppler display shows a wind direction change within a distance of two miles. The bottom scale indicates radial winds in m/s (multiply by approximately 2 to obtain knots). (From ref. 3.)

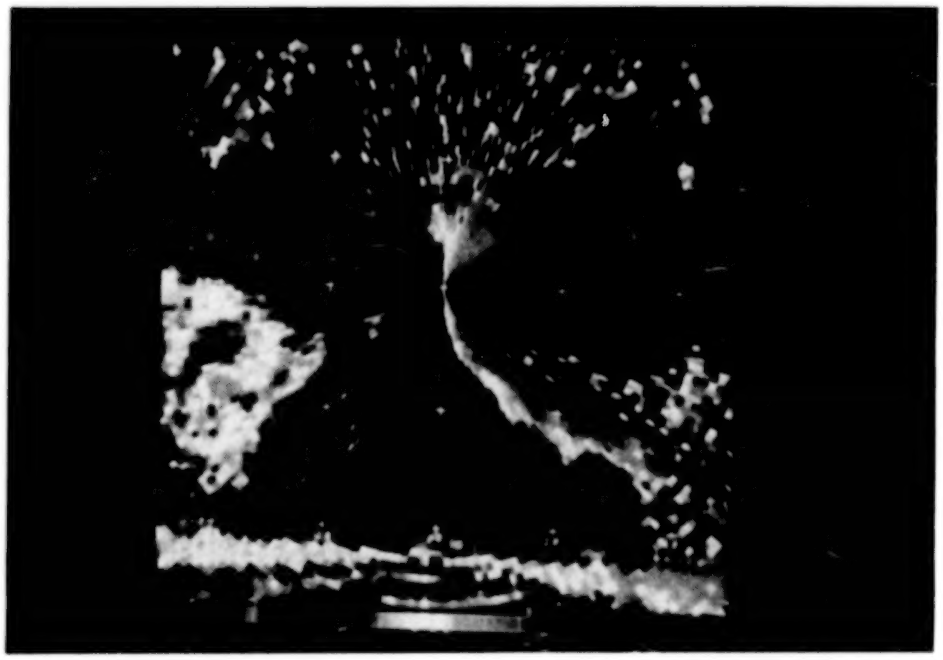

Figure 5. A direct hit of a microburst is shown as seen by the airborne Doppler radar aboard the NOAA P-3 aircraft, looking straight down from 20,000 ft.

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Figure 6. Example of traditionally avoided weather hazard.

Figure 7. Picture by T. T. Fujita, University of Chicago, showing benign-looking high-based virga over Stapleton with no thunderstorm.

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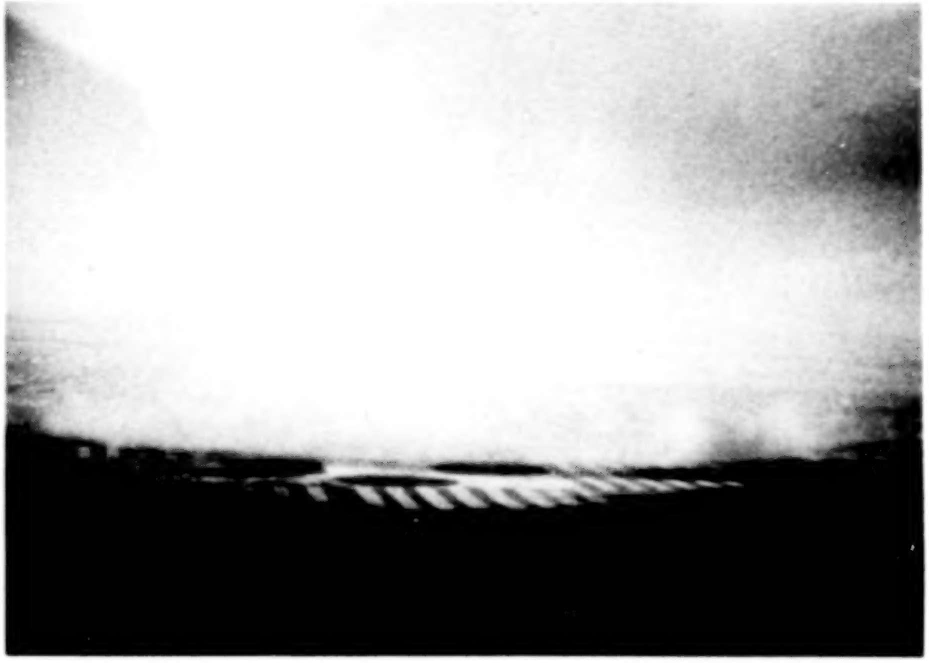

Figure 8. Picture of high-based virga and a dust cloud on the ground; while benign appearing, probably conceals dangerous wind shear.

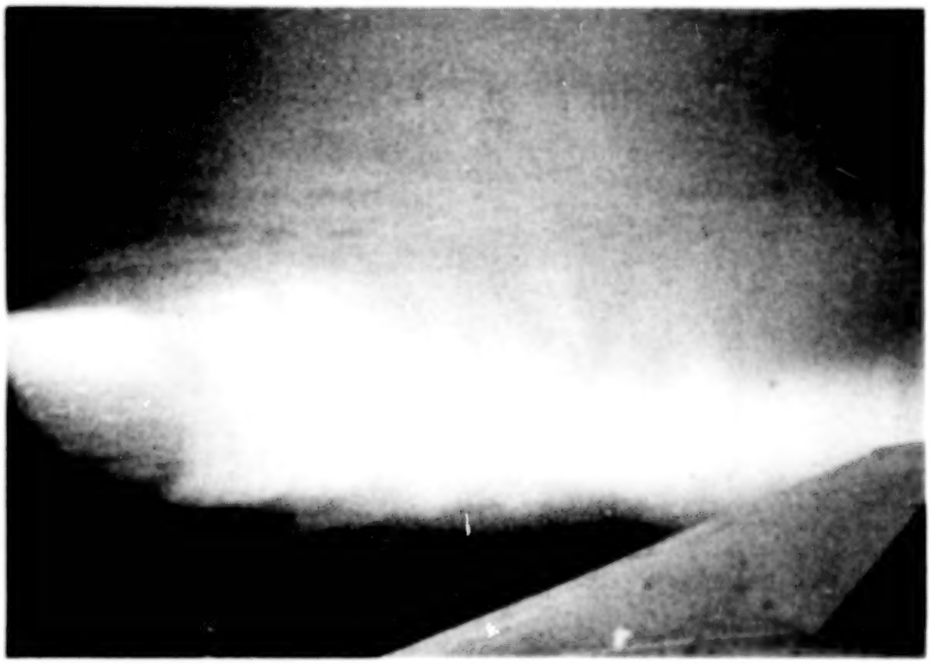

Figure 9. Microburst embedded in heavy rain, similar to the Pan Am 759 or Eastern 66 situation.

Figure 9 is much more like Pan Am 759 or Eastern 66 with heavy rain. There happens to be a microburst in there, but all you see is the heavy rain. You have to be aware of both situations. Figure 10 shows a ring of dust, a picture taken during JAWS in a microburst. Another picture, Figure 11, shows the incredible vortex circulation associated with the leading edge of a microburst.

Finally, Figure 12 shows a downdraft, an outflow, which is described by the author of this print, published in England in 1671 (ref. 4). We think we are pretty smart, but the downdraft is not new!

Figure 13 shows the biggest microburst hit of the summer which occurred directly over Stapleton. An 85 kt differential along the runway axis was measured between two stations approximately one runway length apart. This means that there is an 85 kt loss in head wind component if you choose to go in either direction down runway 35 or 17.

One of the things that I have recently tried to do is document microburst events (ref. 5). Many of these are out of the National Academy report (ref. 6). Our reporting base is the United States to a large degree. Documented are: A) the confirmed microburst events; B) what we think were microburst events; and C) what might have been a microburst event. The worldwide distribution is significantly less. We don't think our document is complete by any means, but the view is that microbursts are occurring anywhere where convection can occur. We feel pretty certain about that. Time of day at Denver--clearly afternoon convection. No big surprise. Our thunderstorms occur in the afternoon at Denver. At Chicago, they are more likely to occur at night. That's when the maximum number of thunderstorms occur at Chicago. Those are the only two locations where any kind of high-resolution system has been set up to look at microbursts. Beyond Chicago and Denver, we don't know the frequency of microbursts, although we think it's a lot higher than we ever imagined.

Some basic statistics from JAWS: the maximum observed by Doppler radar average is 24 m/s, or approximately a 50 kt differential between the two outflows from the microburst. That is, the velocity change from peak positive to peak negative averages about 24 m/s. When they are first detected by Doppler, they are a little less than 2 km across, and at their maximum intensity, they appear to be about 3 km or nearly 10,000 ft. across. They are small. They last somewhere between five and 10 minutes before they become large-scale flows or before they dissipate. If you look at all the velocity differentials for all of the cases that we saw on Doppler radar, you end up with an average of again about 25 m/s, and the maximum that we have clearly been able to measure was about 48 m/s differential, which is 107 mph. The Pan Am 759 microburst as documented by three different sources is 24.5 m/s. So, it was an average value for a JAWS microburst at Denver that brought down Pan Am 759.

If you look at radar reflectivity or classical intensity as a function of wind speed difference, over half of our microbursts occurred in nonthunderstorm situations. All of them occurred with rainfall or virga, but our strongest microburst occurred in a nonthunderstorm situation. So, classical thunderstorm wisdom does not necessarily buy you a thing in terms of avoiding microbursts.

Of 97 microbursts in this particular statistic, a new and very full-circle kind of finding is that 60% occurred in the vicinity of gust fronts. About 25% of them occurred in families, i.e., where one occurred, many more were going to occur. Some of them were associated with gravity waves.

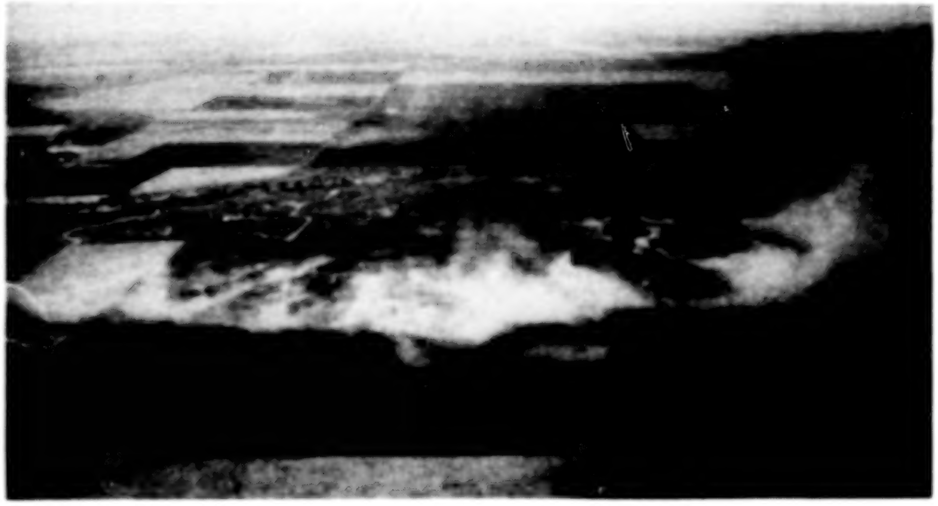

Figure 10. Ring of dust from outflow of a microburst .

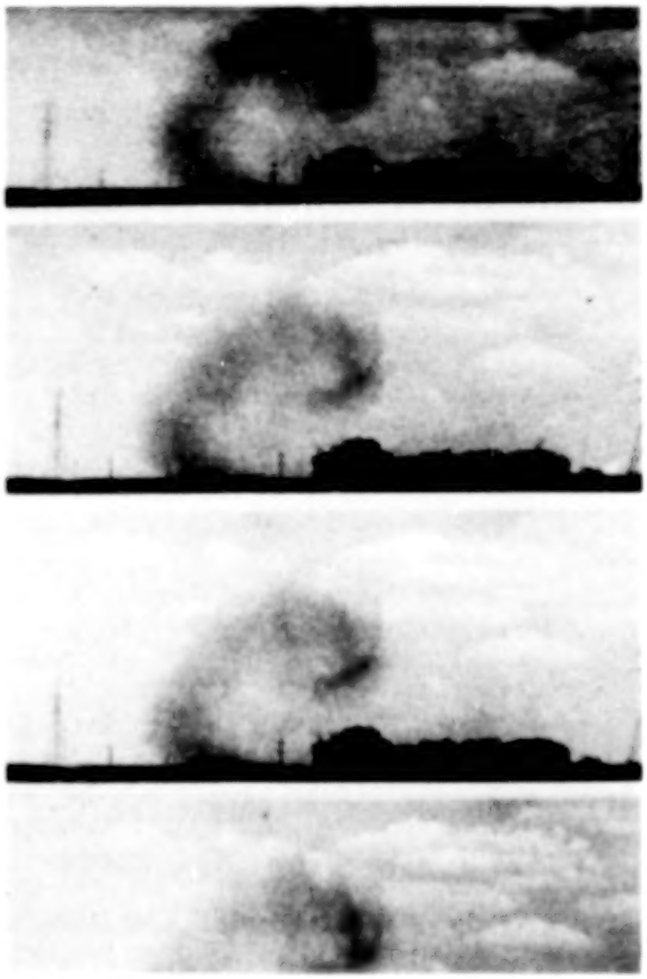

Figure 11. Picture depicts the incredible vortex circulation associated with the leading edge of a microburst.

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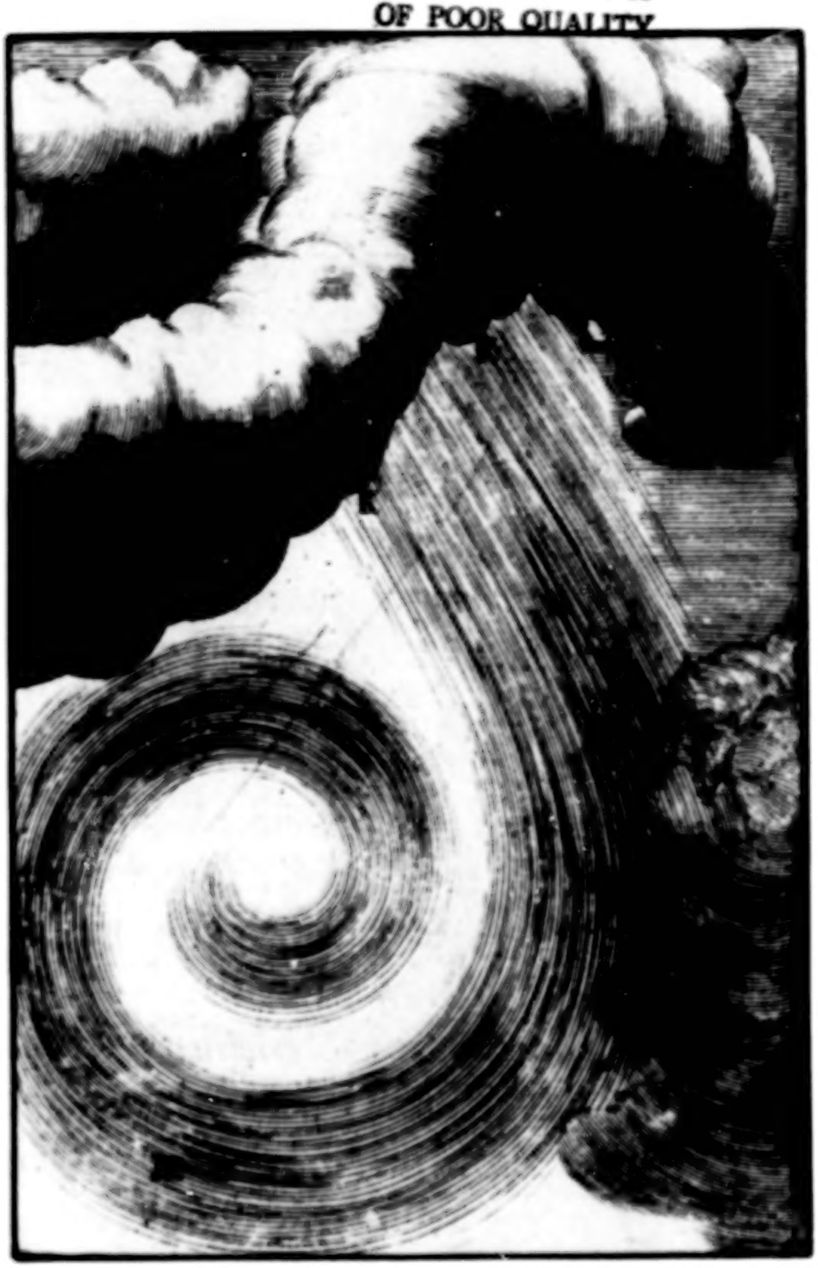

Figure 12. Oxford fellow R. Bohun wrote A Discourse Concerning Origine and Properties of Wind in 1671 (ref. 4). He describes a sudden puff of wind that descends violently down perpendicularly toward the earth. While we take liberties with his description, his drawing is certainly suggestive of microburst features.

The beginning of what multiple Doppler radar will tell you is that on a very high resolution, we can give you what a microburst wind field looks like. There is horizontal flow near the ground with outflow in all directions. The outflow is not uniform and it is not symmetric.

The LLWSAS was looked at very heavily and the results are reported in reference 7. Figure 14 is the distribution of LLWSAS alarms by time of day for the summer of 1982; this is not the distribution of microbursts by day over the airport. The two distributions are different. The resolution of the LLWSAS is 3 km - 6 km, microburst resolution is 1 km - 3 km. So, there are some problems in the algorithms and in the network geometry. We are trying to help in that situation.

NCAR is also peripherally involved in trying to deal with where to put a Doppler radar near an airport, if FAA continues to develop a terminal Doppler radar. I thought I would show you the scenario in Figure 15, which is kind of exciting. The microburst on 14 July occurred off the east end of the runway. The Transportation Systems Center at DOT, Boston, has put together an hour's worth of air traffic movements at Stapleton during this microburst encounter. A Frontier aircraft on approach drops from 700 ft. to 300 ft. in seven (7) seconds, executes a missed approach, and reports the incident on the radio at the same instant the LLWSAS went off. So, they both saw it together. We would like to see it somehow different from that. American 17 right behind Frontier encountered the some thing with a missed approach. Frontier 244, however, didn't believe it yet, so he came back and got back in line and made another missed approach at 2:13 p.m. American 17 didn't believe it either and got back into line for another missed approach, along with a third aircraft. They decided at that point they didn't like runway 26 left, so they decided to come around to 08. The first aircraft through is American 17, who encountered a wind shear at 50 ft., decided he didn't like 08. Of course, they then tried runway 35. At the time they just opened 35 approach, a microburst occurred on the north but now there was nothing on the south end. Continental 414 then approached and got a "sinker" followed by Western 364 who verified a "sinker." After that, operations at Stapleton Airport were closed for about 30 minutes.

Currently, we have analyzed in detail an August 5 microburst case. Data is resolved to a 150 m x 250 m grid. We are currently developing wind profiles from these data and flying aircraft through them with head wind, downdraft, and tail wind. These are the basic wind shear models that we are talking about at this workshop. We have wind fields that are derived from multiple Doppler radar to give you this kind of resolution for three-dimensional and four-dimensional winds. We have a case coming off the press now which gives you a snapshot of the microburst every two minutes for eight or nine minutes total time. You can see the microburst forming and descending, and nobody has really looked at it yet except for us. There have been simulations with a computer model (ref. 8) as to what happens to an airplane when penetrating these winds. These are the data sets that we are preparing for the simulation community.

We have developed a training slide which says that we are convinced that some microbursts can only be flown if some sort of energy trade procedure is flown; and some microbursts, we believe, cannot be flown at all--although we have not proven that yet. Dave Simmon from United presents information to suggest that there are certain procedures that will at least get you through quite a few microbursts (ref. 9).

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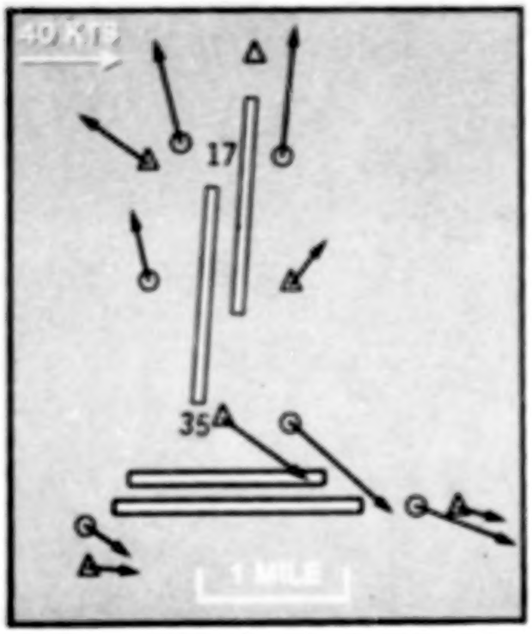


Figure 13. This was the biggest microbust during the summer of 1982 which occurred directly over Stapleton. An 85 kt differential along the runway axis was measured between the two stations, approximately one runway length apart. An aircraft would experience an 85 kt loss in head wind component along runway 35 or 17.

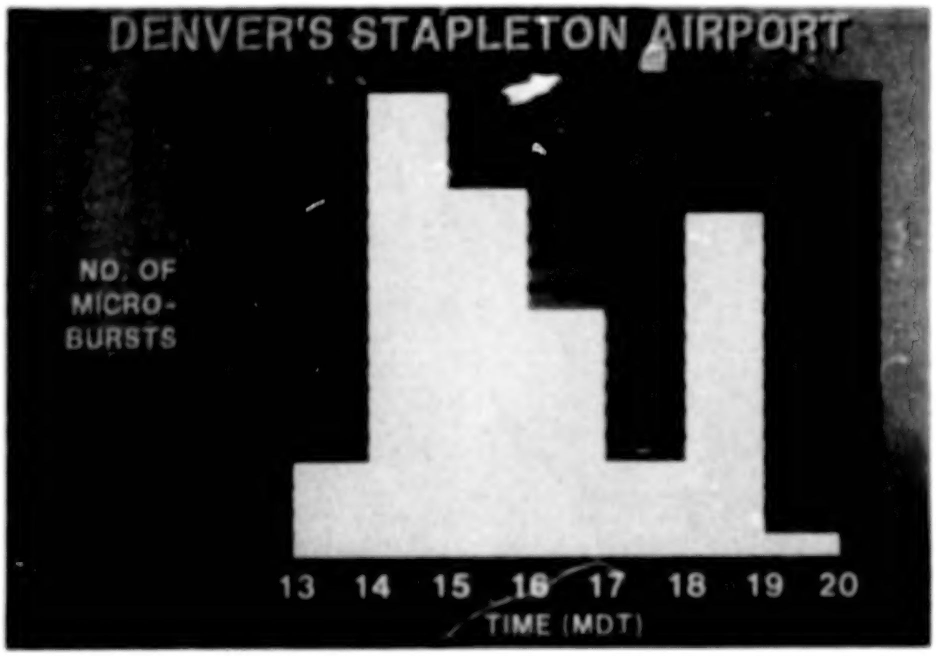
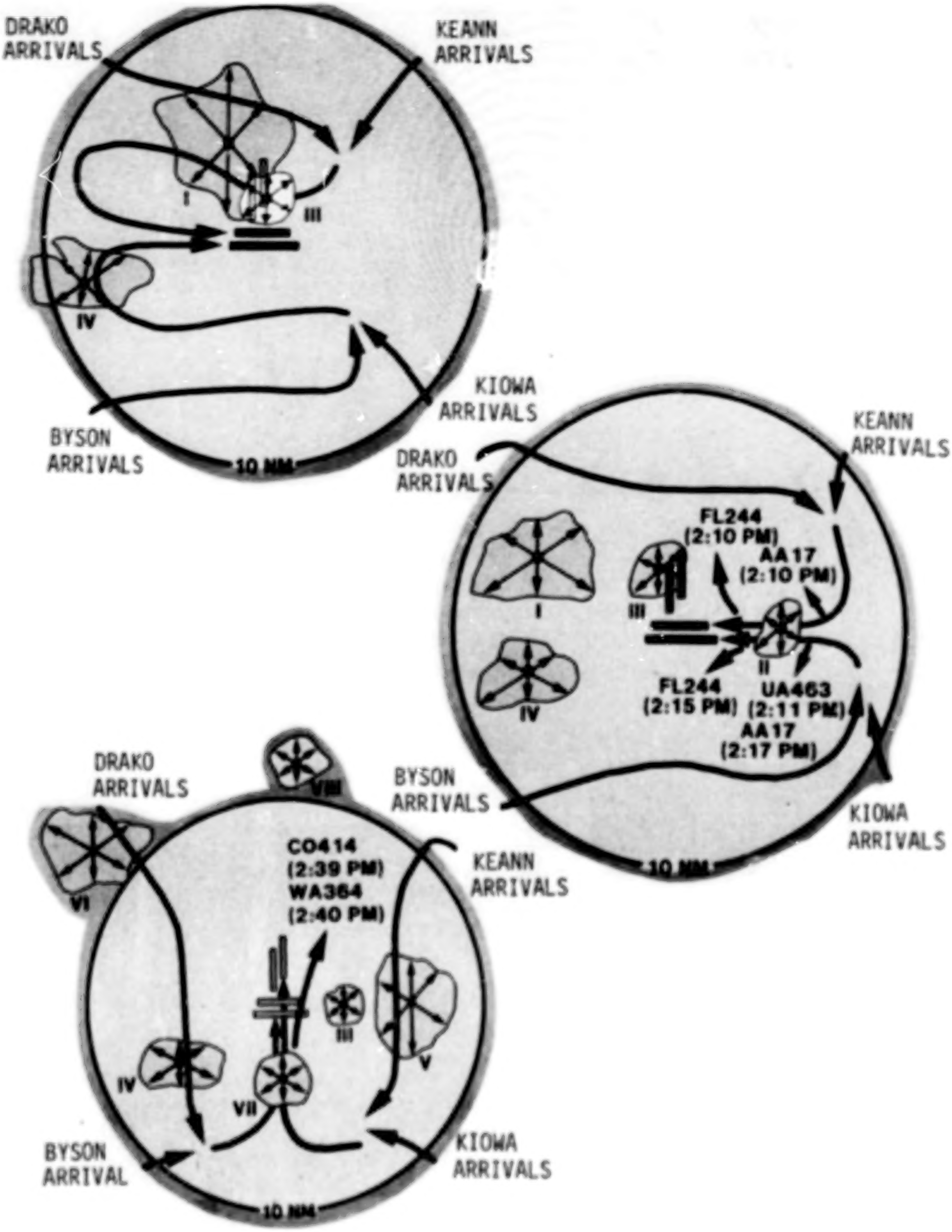


Figure 14. Distribution of LLWSAS alarms by time of day for JAWS during the summer of 1982.


DRAKO ARRIVALS
KEANN ARRIVALS
I
II
III
IV
BYSON ARRIVALS
KIOWA ARRIVALS
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DRAKO ARRIVALS
KEANN ARRIVALS
FL244 (2:10 PM)
AA 17 (2:10 PM)
I
III
II
IV
FL244 (2:15 PM)
UA463 (2:11 PM)
AA 17 (2:17 PM)
BYSON ARRIVALS
KIOWA ARRIVALS
10 NM
DRAKO ARRIVALS
VIII
VI
CO414 (2:39 PM)
WA364 (2:40 PM)
KEANN ARRIVALS
III
V
IV
VII
BYSON ARRIVAL
KIOWA ARRIVALS
10 NM

Figure 15. July 14 microburst events over and near Stapleton Airport, showing an hour's worth of air traffic movements at Stapleton during the encounter as described by the DOT Transportation Systems Center. There were several close calls, and numerous missed approaches (sequence of three pictures).

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JAWS MULTIPLE DOPPLER DERIVED WINDS

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Joint Airport Weather Studies Project
National Center for Atmospheric Research

INTRODUCTION

This paper is designed to give an elementary working knowledge of the advantages and limitations of the multiple Doppler radar analyses that have recently become available from the Joint Airport Weather Studies (JAWS) Project. The emphasis is specifically directed towards engineers and other technical specialists working in aviation-related systems rather than research institutes. The paper addresses what Doppler radar is and what it does and describes the way Doppler radars were used in the JAWS Project to gather wind shear data. The working definition of wind shear used here is "winds that affect aircraft flight over a span of 15-45 seconds," whereas turbulence is defined as "air motions that cause abrupt (several seconds or less) aircraft motions." The JAWS data currently available contain no turbulence data.

The concept of multiple Doppler analysis and the geometry of how it works are described, followed by an explanation of how data gathered in radar space are interpolated to a common Cartesian coordinate system and the limitations involved. This section includes a discussion of the analysis grid and how it was constructed. What the user actually gets (quasi-horizontal wind components) is discussed, followed by a discussion of the expected errors in the three orthogonal wind components. The paper concludes with a discussion of why JAWS data are significant.

Although this paper is not intended to be an exhaustive treatment of Doppler radar technology and techniques, it will focus, in a very basic way, on the concepts needed to understand what JAWS can and cannot provide in the area of observed wind shear data.

DOPPLER RADAR: WHAT IS IT?

Like a Doppler radar, a standard, or incoherent, weather radar transmits a very short (about a microsecond long) pulse of electromagnetic energy and then listens for a relatively long period (roughly a millisecond) for any echoes. By carefully timing how long it takes to receive any echoes, the range to the echo can be determined very precisely. The direction of the echo from the radar is established by where the antenna is pointing when the echo is received as the antenna doesn't move a significant amount from the time of transmission to the time of echo reception. Some idea of the size and number of echo-producers--targets--can be determined if something is known about their physical makeup, e.g., liquid water, wet ice (as in hail), snow, or, in the case of non-weather radar, metal. For rain, the stronger the signal returned, the larger the raindrops.

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A lot can be learned about targets using an incoherent radar, but target motion relative to the radar cannot be obtained directly. If it's a large single-point target, like an airplane, we can determine which way it's going and how fast after a minimum of only two scans by the radar--we can watch it move. But in the case of meteorological echoes, which are made of thousands of targets far smaller than the radar can resolve individually, we cannot know whether the particles are moving relative to the storm they make up. We can only know whether the entire storm is moving.

A Doppler, or coherent, radar does exactly what an incoherent radar does plus one other function: it measures how fast a target is moving toward or away from the radar by measuring the Doppler phase shift of the received signal. The speed radar used by police is a very simple version of the kind of radar used in the JAWS Project. The term coherent indicates that the phase of the transmitted radar signal is coherent from one pulse to the next; and so any phase shift in the returned signal can be measured and converted to engineering units of meters per second or knots. Since Doppler frequency shifts are so small at the speeds meteorological knots move and at the frequencies meteorological radars operate, phase shifts rather than frequency shifts are measured. Regardless of whether phase or frequency shifts are measured, the Doppler concept remains valid. Because a Doppler shift relative to the radar is used to measure velocity, we see that the target must have some component of motion toward or away from the radar to register a non-zero velocity. A Doppler radar can only measure the radial component of motion toward or away from it--any tangential component cannot be observed.

Data collected by a pulsed Doppler radar are described in terms of beams and gates (gates are often interchangeably referred to as pulse volumes). A Doppler radar operating with a stationary antenna maintaining a constant azimuth and elevation angle transmits a pulse of energy which, as it travels out, traces a beam. Due to the nature of the antennae currently in use on the JAWS radars, the beam is not perfectly collimated like a laser; it spreads out, getting wider the further it gets from the radar. This spread is called the "beam-width." For the JAWS radars, the beam-width is very nearly 1 degree; and at ranges greater than about 10 km becomes the limiting factor, restricting what spatial scales the radar can resolve.

A receiver can be gated so that the waiting time for echo return is at approximately one-microsecond intervals. The pulse has time to travel out to and return from a range of 150 m (total distance of 300 m) in the first microsecond, 300 m in the second, 450 m in the third, etc. A beam gated into discrete 150 m segments effectively defines a string of volumes that look like segments of a 1-degree cone, each segment 150 m long. These segments are what radar meteorologists refer to as "gates" and/or "pulse volumes."

Finally, the reflectivity and velocity data that a Doppler radar gathers are the ensemble average of what's in each gate. Thus, we measure what raindrops are doing on the average within each gate--there could be a tornado completely contained within a gate and the velocity data gathered by a Doppler radar would still reflect the average velocity within that gate.

MULTIPLE DOPPLER

Assume that we have two Doppler radars with beams oriented in a fashion similar to Figure 1, and that the antennae are pointing locally parallel to the earth's surface. At the point where the two beams intersect, each Doppler radar is measuring the radial velocity towards it. Figure 2 shows what radar A would measure in the gate coincident with the intersection of the two radar beams. For the sake of this example, assume further that radar B also has a gate coincident with the intersection of the two radar beams; Figure 2 also shows what radar B measures in the gate coincident with the intersection of the two radar beams. Obviously, only simple geometry is required to resolve the two radial components measured by the two radars into two orthogonal components, as shown by the inset. Quite simply, this is how two Doppler radars are used to define the quasi-horizontal wind at the surface. But in reality, the process is much more complicated.

INTERPOLATION FROM RADAR TO CARTESIAN SPACE

A radar gathers data in a spherical coordinate system defined by azimuth, elevation, and range with the radar at the coordinate system origin. Since each radar works in its own coordinate system, a coordinate system common to both radars is required. The common coordinate system used is standard three-dimensional Cartesian space. For JAWS data, the x-direction is always positive towards the east, the y-direction, positive towards the north, and the z-direction, positive upward. As an example, a positive x wind component indicates that the wind is blowing from the west.

The process of mapping radar data onto a Cartesian coordinate system is called objective analysis. Figure 3 shows a two-dimensional schematic view (not to scale) of radar data overlaid by a regular Cartesian grid. Each little square box signifies a gate of radar data and each plus-sign symbol signifies a Cartesian grid point or "node." There are many ways to perform an objective analysis, but all address the question of how best to derive a value at some grid point that is most representative of the surrounding data. We utilize a standard method called Cressman analysis that uses a distance-weighted mean computation.

Figure 4 shows a close-up of nine grid points where the center grid point has been surrounded by a circle of influence whose radius equals the Cartesian grid spacing. All radar gates within this radius of influence contribute to the final value that is ultimately applied to a particular grid point and is representative of the data around it. Note that in using this method some gates will affect as many as four different grid points.

The weighting function to determine how much a given datum affects its associated grid point is given by

$$g_i = \begin{cases} \dfrac{R_r^2 - d_i^2}{R_r^2 + d_i^2} \, , & d_i \leq R_r , \\ 0 \, , & d_i > R_r \end{cases} \tag{1}$$

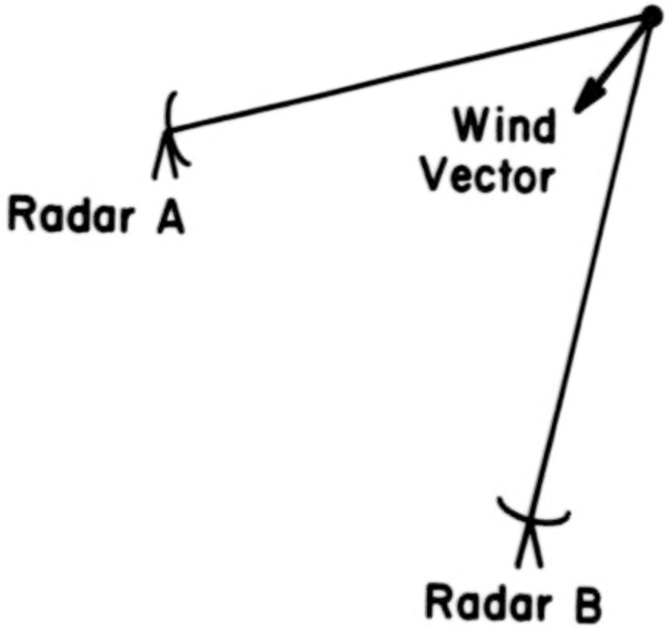
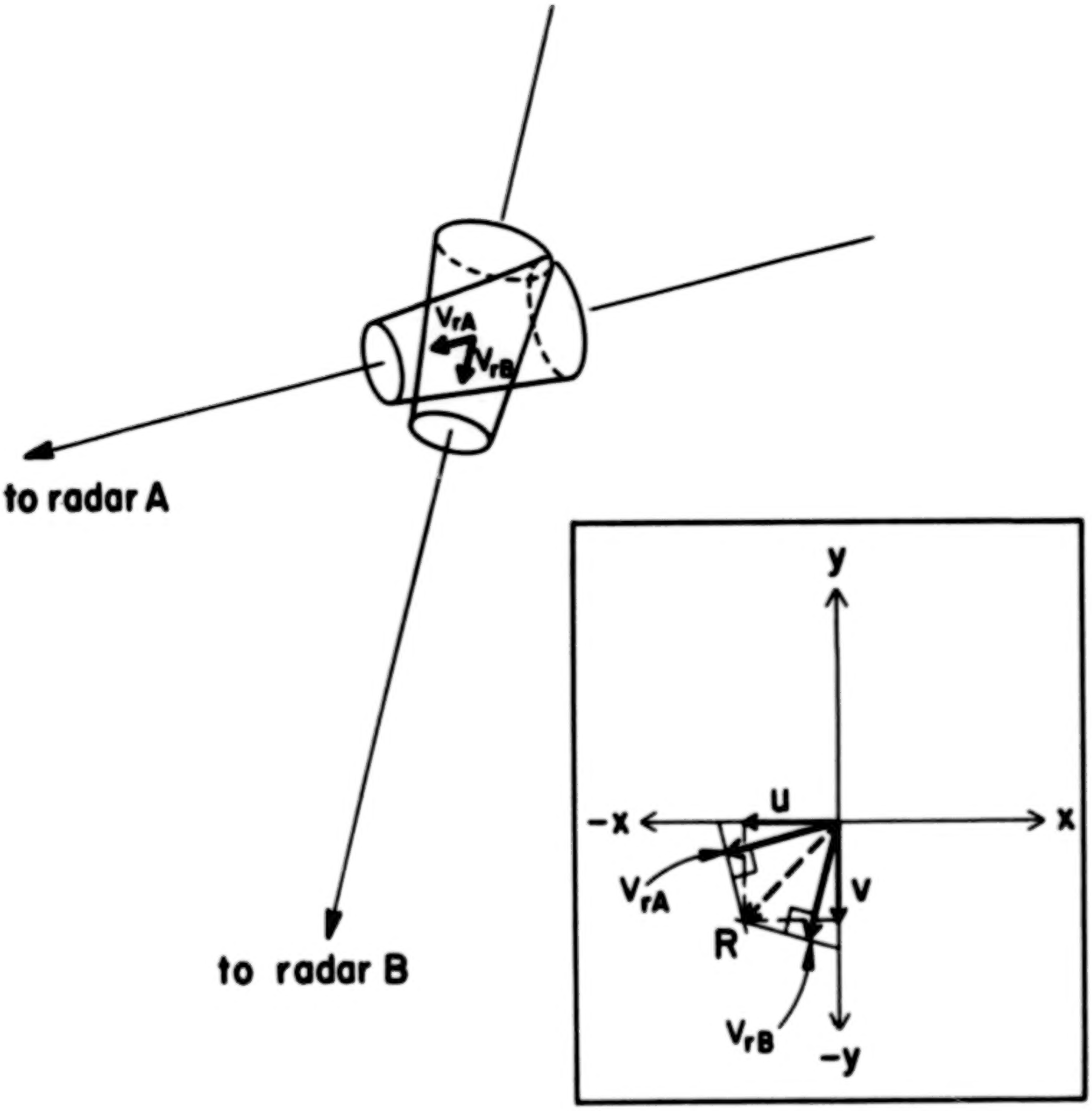

Wind
Vector
Radar A
Radar B

Figure 1. Two Doppler radars sampling a common point in space.



VrA
VrB
to radar A
to radar B
y
u
-x
x
VrA
v
R
VrB
-y

Figure 2. The resolution of V_{rA} and V_{rB} into orothogonal components. Inset shows graphical resolution of two non-orthogonal into two orthogonal components using direction cosines.

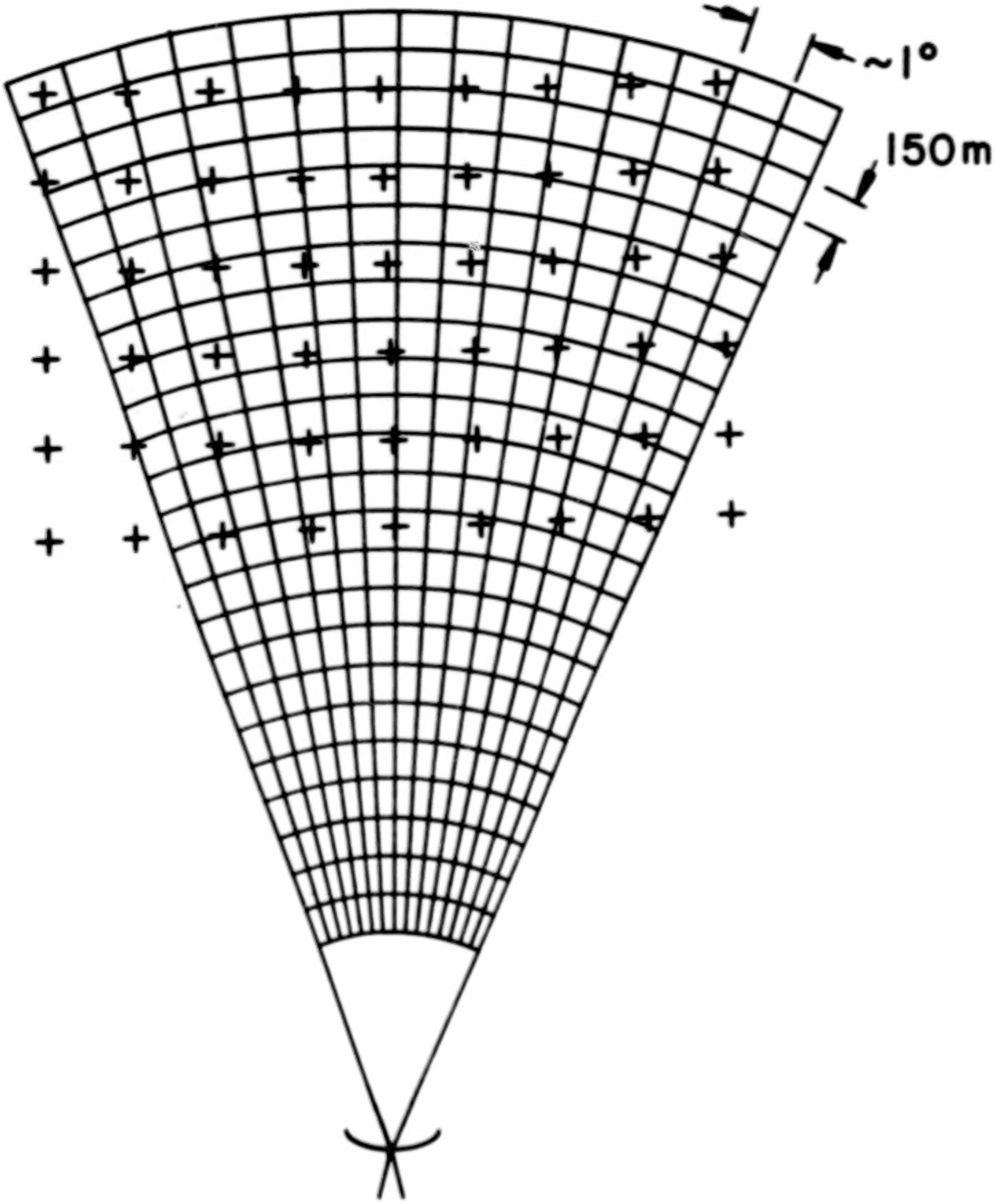


Figure 3. Two-dimensional schematic view (not to scale) of Doppler radar data overlaid by an orthogonal Cartesian grid.

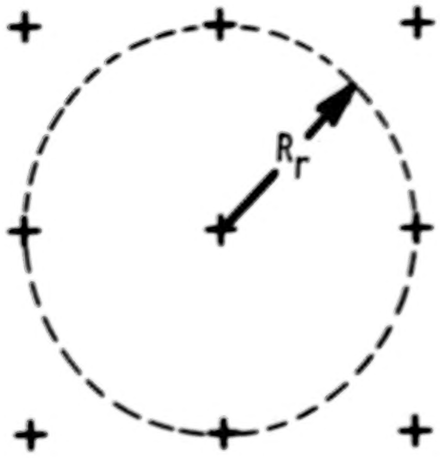


Figure 4. A close-up of the Cartesian grid point that is used in a Cressman objective analysis scheme.

where g_i is the weight of the i th datum, d_i is the distance from the grid point to the i th datum, and R_r is the radius of influence which, for our case, is equal to the grid spacing.

An objectively analyzed grid point value is defined as

$$G = \frac{\Sigma V_r(i) g_i}{\Sigma g_i}, \tag{2}$$

where G is the objectively analyzed grid point value, $V_r(i)$ is the value of the i th datum, and g_i is the weight assigned to the i th datum. In reality, radar data are three-dimensional, not two-dimensional, and an influence volume, rather than an influence circle, is used. The influence volume is spheroidal in shape, since the Cartesian grids we use may not always have the same vertical and horizontal spacing.

This objective analysis is performed on the radial velocity and reflectivity data gathered by each radar. Thus, at the end of the objective analysis step we will have fields of radial velocity and reflectivity from each radar all on a common grid. Both the radial velocity and reflectivity are used in the next step: three-dimensional wind field synthesis.

THREE-DIMENSIONAL WIND FIELD SYNTHESIS

We want to synthesize the horizontal wind components u and v, as well as the vertical wind component, from only two knowns (radial velocity from each of two radars). It would seem our system of equations is seriously underdetermined, but this apparent dilemma is solved using the equation of continuity.

In its simplest terms, the equation of continuity states that whatever goes into a volume must come out of it somewhere else, thus conserving the mass within the volume. The volume may not accrue a mass excess or suffer a mass deficit. Figure 5 shows the concept schematically. For this example, assume that the bottom of the box is a solid boundary, like the ground. Since air cannot go into or come out of the ground, whatever enters the top of the box must exit out the sides (divergence). Conversely, if air enters the sides of the box (convergence), air exits through the top.

The radial velocity measured from any radar, i, is given by

$$V_i = \frac{1}{R_i} \left(ux_i + vy_i + Wz_i\right) \tag{3}$$

where i is the radar index, x_i, y_i, and z_i are the Cartesian distances from the pulse volume to the i th radar, W is the vertical motion of the raindrops measured by the radar, and R_i is the slant range from radar i to the pulse volume, defined as

$$R_i = x_i^2 + y_i^2 + z_i^2 .$$

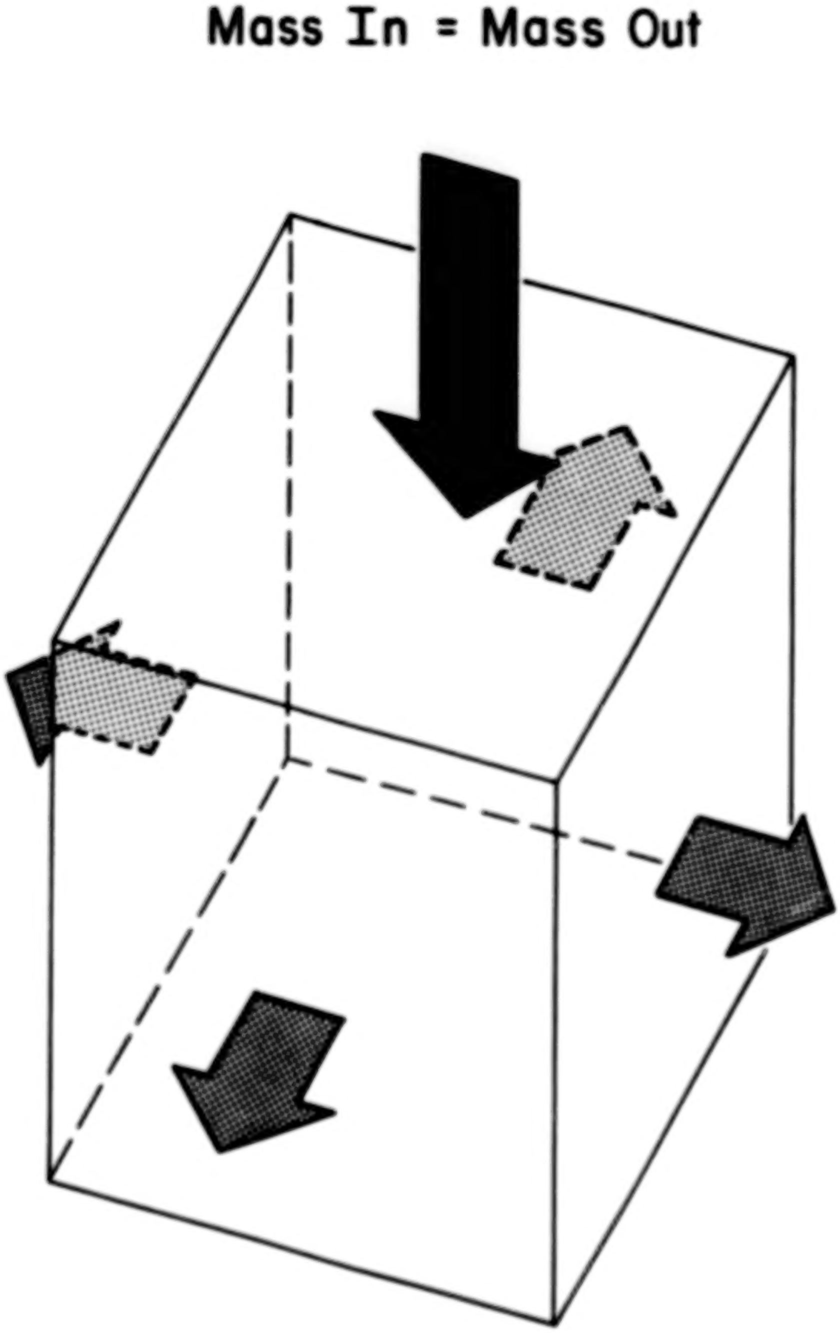

Mass In = Mass Out

Figure 5. The concept of continuity as it applies to JAWS analysis.

A radar actually measures the motion of raindrops, but what we really want is the air motion. Studies have shown that raindrops are remarkably good tracers of horizontal air motions, but they tend to fall at speeds that are on the order of the vertical airspeed; therefore, they make poor vertical air motion tracers. Thus, vertical fall speed somehow must be accounted for since we really want the motion of the air, not of the raindrops.

Recall that reflectivity can be used to estimate the size of the raindrops. By knowing their size, we can estimate quite well how fast they are falling through the air. With this estimation, we can correct the radial velocity from each radar to make a better estimate of the actual air motion, uncontaminated by the fallspeed of the raindrops.

So W in Equation (3) can now be broken into two parts: w, the actual vertical air motion and V_t, the terminal fallspeed of the raindrops. The equation describing terminal fallspeed has the following form:

$$V_t = -3.8 \left(\frac{\rho_{sfc}}{\rho(z)}\right)^{0.4} Z_e^{0.0174} \tag{4}$$

where $\rho(z)$ is density at some height z, ρ_{sfc} is density at the surface, and Z_e is the equivalent radar reflectivity. Finally, the form of the continuity equation used for JAWS is the anelastic (or compressible) continuity equation, given by

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = -\frac{w}{\rho}\frac{\partial \rho}{\partial z} . \tag{5}$$

We now have four equations, (3)-(5), (since (3) counts as two equations), and four unknowns, u, v, w, and V_t.

Given the equation for V_1 and V_2 (the radial velocity from each radar), the equations for u and v become

$$u = A + B(w + V_t), \tag{6}$$

$$v = C + D(w + V_t), \tag{7}$$

where

$$A = \frac{R_1V_1y_2 - R_2V_2y_1}{x_1y_2 - x_2y_1}, \tag{8}$$

$$B = \frac{-z_1y_2 - z_2y_1}{x_1y_2 - x_2y_1} , \tag{9}$$

$$C = \frac{-R_1V_1x_2 + R_2V_2x_1}{x_1y_2 - x_2y_1}, \tag{10}$$

and $D = \frac{z_1 x_2 - z_2 x_1}{x_1 y_2 - x_2 y_1}$. (11)

We use Equation (4) to eliminate V_t from Equations (6) and (7), and then integrate Equation (5) to yield

$$w_k = w_{sfc} \frac{\rho_{sfc}}{\rho_k} - \frac{1}{\rho_k} \int_{sfc}^{z_k} \rho(z) \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) dz \ , \tag{12}$$

where subscript sfc indicates a boundary (surface value), subscript k indicates the grid level for which the computation is being carried out, ρ is density, and $\rho(z)$ is the density at any height z.

In Equations (6) and (7), u, v, and w are all functions of each other and so are solved using an iterative predictor-corrector process. Starting at the bottom of the data (the surface), we assume w = 0. Based on this assumption, we solve for u and v. Then w at the next level up is specified using w at the previous level as a first guess. Since we've specified w at this k = 2 level, we can compute u and v as we did at the surface. We now have u's and v's at two levels, so we can use them to compute a divergence over the depth from the surface to the second grid level. We then integrate this divergence over this depth using a numerical approximation of Equation (12) and come up with a new w at the second level. This new w is used to compute a new u and v at the second level, which is, in turn, used to compute a new divergence, and so on until divergence, and so w, converges on some constant value. Then the process repeats between the second and third levels, then the third and fourth levels, etc., until the top of the data is reached. The iterative process described above usually converges after about five to seven iterations for each level.

ERRORS

Comparing the numbers derived from these equations with the real world, the horizontal wind components are good to about 2 kts and the vertical wind component is good to about 6 kts, depending upon how far above the ground the measurement is made. Errors result for several reasons. The radar itself can measure velocity inside a gate or pulse volume to within 0.02 kts, but not everything in a pulse volume is moving in unison. The radar calculates a number that represents only the ensemble average motion of all the raindrops in the gate. Therefore, a radial velocity estimate within each individual pulse volume is good to roughly 0.5 kts.

We have to interpolate radial velocities from radar (spherical) space to a regular, common Cartesian grid. This is the most costly step in terms of accuracy. The interpolation process along with previously mentioned effects yields gridded radial velocities good to a little less than 2 kts.

With these errors, we synthesize u and v. Each of the radar beams is not always perpendicular; in fact, that is an extremely rare event since it occurs at only two points. Also, the radial velocity from each radar is not measured at the same point in space at the same time. Finally, it takes a finite amount of time (about 2 minutes) to gather all the necessary radial velocities from each radar over the region of interest. This can be likened to "moving the camera" while taking a photograph; it tends to degrade the quality of the picture. Yet, given all this, u and v are still good to just a little over 2 kts.

In computing w, we have additional problems. First, we compute derivatives using a three- or five-point numerical finite difference which has well-known error properties. Next, we integrate these derivative estimates vertically upward from a known boundary condition using density weighting. Because of the density weighting, any errors in w made at low levels will be amplified as we integrate upward because an error in w really translates into an error in mass flux. The mass flux error actually remains constant as we go upward, but because density decreases upward, a larger w is required to maintain the same erroneous mass flux.

In all cases, we assume that w at the ground is zero, which in and of itself is a very good assumption. But, in fact, the lowest data level gathered by a Doppler radar is not at a height of zero meters; it is usually at least a few meters above the surface and can be tens of meters above the surface. Obviously, w is not zero a few meters above the surface, and this is a source of bias error in w. Orography can also play a role in degrading w. For example, if horizontal windspeeds at the surface are 40 kts and the terrain slopes at an angle of two degrees (a 3.5% grade), w at the surface will be 1.3 kts. This will substantially bias w at the higher levels.

Because w is a derived quantity, it is the least accurate. At the top of the data (roughly 3000 feet AGL), w is good to only about 6 kts. However, near the ground, where approaches and takeoffs are simulated, w is very nearly as good as u and v.

The following table summarizes the expected errors in JAWS data:

PARAMETER IN ERROR	MAGNITUDE	SOURCE(S)
fundamental radial velocity (pulse volume)	∿0.5 kts	mainly turbulence
gridded radial velocity	<2 kts	interpolation
u and v	∿2 kts	all data not simultaneous in time and space
w	∿2-6 kts (height dependent)	1) truncation errors 2) improper boundary conditions

JAWS has independently verified these u, v, and w velocity estimates with airborne, vertically pointing Doppler radar and in situ, instrumented aircraft measurements; thus their accuracy, at least in cases we have been able to compare, is within the limits given above [1].

WHY JAWS DATA ARE SIGNIFICANT

A comparison of flight data recorder (FDR) reconstructions with JAWS multiple Doppler data reveals advantages unique to the FDR reconstructions:
1) FDR data come from wind shear that presumably caused the crash; and
2) FDR resolution is, in a sense, better than Doppler data since FDR's collect data at a frequency of 1 Hz, which at an approach speed of 150 kts, corresponds to a spatial resolution of 75 m compared to 150 m for Doppler data.

However, on the multiple Doppler data side, advantages include: 1) actual winds are measured; 2) few assumptions are required to obtain all three wind components; and 3) multiple Doppler radar analyses are fully three-dimensional.

The only obvious disadvantage to a multiple Doppler radar analysis is the best fundamental resolution of the instrument, which is 150 m compared to FDR resolution which is roughly 75 m. However, FDR disadvantages are somewhat more serious. The older FDR's, from which most accident reconstructions come and which make up the vast majority of FDR's flying today, are not very accurate. FDR's do not measure the actual winds; the winds must be derived through a complicated process involving many, often crude, assumptions. Finally, and most importantly, FDR's provide only one-dimensional data--a noodle along the aircraft's final path. The real world that we fly in is fully three-dimensional; for realistic simulations and control analysis, the input winds must also be three-dimensional. Multiple radar analyses provide a sufficiently better product for aviation uses than previous FDR reconstructions that a sizable implementation and utilization effort is warranted.

The following table will help in summarizing the pros and cons of FDR reconstruction vs. multiple Doppler analyses.

FDR ADVANTAGES	DOPPLER DISADVANTAGES
Data came from wind shear that presumably caused the crash.	
In a sense, better one-dimensional (along track) resolution (75 m).................	Data only every 150 m (492 ft)

DOPPLER ADVANTAGES	FDR DISADVANTAGES
	Old FDR's not very accurate
actual winds are measured.......................	Actual winds not measured--must be derived
few assumptions required to get all three components...........	Derivation of winds requires too many, often crude, assumptions
fully three-dimensional.........................	only one-dimensional.

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STATUS OF THE JAWS PROGRAM

John McCarthy
Director, JAWS Project
National Center for Atmospheric Research

The preliminary data description of the August 5, 1982, microburst case is available (ref. 1). We need to discuss its use. The turbulence part, however, is not yet out.

Let me tell you basically what our simulation accomplishments have been from our perspective at the National Center for Atmospheric Research (NCAR). We have prepared and distributed through this forum and on tape the August 5, 1982, microburst data set for a single time. It does not include turbulence. It is a one-time velocity and is currently available. We will shortly make available four such velocity fields, two minutes apart, for the same August 5 case, so that the dynamic change of the microburst can be simulated. There is more data than you may want on the August 5 microburst. However, from this case you can see the birth, evolution, and depth of the microburst. The turbulence data is also available for this case.

QUESTION:

There are some other data sets in industry and NASA. You are speaking only of one here. Are you saying that this is probably the best, the most representative one you have? What cautions should we use on some of the other ones?

RESPONSE:

There are two other data sets which have been looked at in a preliminary fashion. The first one was June 29, 1982, which should not, in our opinion, be used because it was the first one we analyzed. We question the accuracy of the data due to problems of resolution caused by the distance from the radar. In general, it is a good microburst, but it does not have the resolution or accuracy of the August 5 case. Another case that was looked at very briefly was the July 14, 1982, case. Another case that was looked and it has not been released for any real use. The only case which we feel is top-notch at this point is the August 5,1847 sequence. There are three other times we have looked at carefully, and they're about to be sent from NCAR through the processing loop to FWG Associates and to NASA for general distribution.

An in-depth analysis of the July 14, 1982, case, which is a moderate case, is basically unfunded. We consider August 5, 1982, to be a significant microburst. The June 30, 1982, case has not yet been distributed, although analyses of it have been done for research and fundamental characterization issues. It is a larger scale flow with a fairly intense mesocyclone in it. It is a very nice case for looking at what might happen if you get into a fairly large flow that has an intense cyclone.

For these cases, the objective is to develop 1-, 2-, and 3-plane slices through the more severe wind shear as sub-volume data set as well as to provide a full-volume data set. They will include three-dimensional time dependent velocities and radar reflectivity intensity when we have it, as well as turbulence data.

There are two major tasks that are currently not funded. The first one is a statistical characterization of all the cases we get a chance to analyze. We measured many microbursts in JAWS. We "saw" at least 75 on Doppler radar. Analyzing these is an intensive job, so there is a limit as to how many we can do. We want a full characterization: how big they are; how asymmetric they are; the maximum/minimum velocities; the vertical velocity structure, etc. One point that Kim did make (ref. 2), and about which misconceptions exist is that the maximum vertical velocity that we are getting at 250 m is about 2,000 fpm. There are values being quoted right now that are three to four times this value. The surface boundary conditions preclude larger vertical velocities than that near the ground. At 250 m, we are seeing about 2,000 fpm down, and this value decreases linearly to zero at the ground. Values different from that are not substantiated by the data. So, the final two tasks, if we can secure support for them, are a full statistical characterization of the cases which we have analyzed with multiple Doppler, and the establishment of a simplified analytical or numerical model of microbursts based on actual JAWS Doppler radar data.

We think that one of the things you are going to need, and which you do not currently have, is a simplified numerical or analytical curve fit of the data sets. The simplified model, in our opinion, does not actually characterize real data. We think we can develop a simple model from curve fit data, however. Figure 1 shows things that we have done or can do. We can look at velocity and turbulence intensity. We have several cases available and more could be made available. Additional support is going to be needed to complete this job.

QUESTION:

Do you have a feeling for both the average and the maximum of both the horizontal and the vertical shears as a function of altitude? You just mentioned one starting at 250 m at 2,000 fpm and decreasing linearly.

RESPONSE:

The maximum that we observed on Doppler and feel comfortable with is a horizontal change of 48 m/s (approximately 100 kts) over about 3 km. The peak of our sine wave or the sawtooth wave that you are using would be 48 m/s amplitude wave. I think that's the maximum that we've observed in JAWS. Now, we know that there is evidence of a stronger microburst. We think the one that hit Andrews Air Force Base was substantially stronger. Of the five cases that we have looked at, the vertical velocity decreases nearly linearly with height from zero at the surface to 2,000 fpm or 11 m/s at 250 m; at 500 m, it could possibly double. Above that altitude, the multiple Doppler analysis technique that we use falls apart, so that above roughly 1,000 m, we don't feel terribly comfortable with our vertical velocity. At the altitudes of approach and takeoff, we feel quite comfortable with it. But note that one of the tasks on Figure 1 is a full statistical characterization for the purpose of simulation, and that is a taks we have not yet done. We don't want to do it until we have analyzed enough cases to develop that body of statistics.

QUESTION:

I think the thing that we need, from the standpoint of training, is a good feel for what some of the outside parameters are. What is the two or three standard deviation value; what are we looking at from the standpoint of downbursts; what are we looking at from the standpoint of horizontal shears? That would be very helpful to us; because, quite frankly, we don't know much to put in our simulator models which we have right now.

- NEW, REAL, 3- to 4-DIMENSIONAL DATA
- LIGHT, MODERATE, SEVERE MICROBURST CASES
- VELOCITY, TURBULENCE, INTENSITY
- SEVERAL CASES AVAILABLE
- MORE CASES COULD BE AVAILABLE
- MODEL SIMPLIFICATIONS COULD BE AVAILABLE
- STATISTICAL CHARACTERIZATION COULD BE AVAILABLE
- MORE GOVERNMENT/INDUSTRY SUPPORT ($) NEEDED TO FINISH JOB

Figure 1. Conclusions.

RESPONSE:

One problem that we aren't going to solve is that we are underestimating the shears. The smoothing that occurs in this analysis underestimates the peak magnitude to some degree, probably 20%, so we know there is some underestimating going on.

QUESTION:

If you conduct an analysis using the continuity equation and consider a continuous flow, and then you limit the downward flow at 250 m, you come up with horizontal outflows that are not nearly on the order of what was estimated to have occurred at Andrews Air Force Base (see ref. 3). Considering that it is possibly a vortex ring, as hypothesized by several researchers, it has a significant effect on analysis. You could have the type of downward flow you are talking about and still generate these extreme horizontal flows very close to the surface. Will you comment on that, please?

RESPONSE:

Continuity still applies, but it only applies to the resolution of your data. If there are some very small-scale flows embedded in there that you cannot resolve, then certainly there could be flows from any source, such as vortex rings, that we aren't resolving. Fluid flow continuity is still valid.

QUESTION:

I agree with that; however, they are assuming a continuous downward flow without the vortex.

RESPONSE:

Assuming a continuous flow is not required. What you are really addressing is resolving a flow smaller than the radar resolution. It is certainly possible that those flows are there and that we cannot resolve them. For this reason, an extremely high resolution experiment is being tried this summer in Boulder to look at 10 m to 100 m resolutions to resolve the small-scale flows. That is not an issue of continuity; it is an issue of the fundamental resolution of your sensor.

QUESTION:

What are you doing in terms of publishing temperature pressure profiles in the microburst environment?

RESPONSE:

We are very close to publishing that data in connection with surface measurements. Of 130 microbursts that have been identified and will be published through JAWS, we are going to characterize all of those parameters show the relationship to the gust front, to temperature, ΔT's, ΔP's, and velocity distributions for direct hit, near-miss, and distant microburst measurements.

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1. JAWS Project Preliminary Data Description. National Center for Atmospheric Research, Boulder, Colorado, Sept. 1983.

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3. Fujita, Tetsuya Theodore: Andrews AFB microburst. SMRP research paper 205, Satellite and Mesometeorology Research Project, Dept. Geophys. Sci., Univ. Chicago, 1983.

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MODELING AND IMPLEMENTATION OF WIND SHEAR DATA

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The problems of implementing the JAWS wind shear data are discussed in this presentation. First of all, I will describe the data sets from the point of view of utilizing them in an aircraft performance computer program. Then I will describe some of the problems of non-standard procedures in terms of programming the equations of aircraft motion when the effects of temporal and spatially variable winds are included. Finally, I will show you some of the computed effects of the various wind shear terms.

The specific tasks to be performed under NCAR contract are listed in Figure 1. The collection and processing of the dual and triple Doppler returns have been described in references 1 and 2. The processing of the Doppler radar signals resolves the data into a rectangular array of three Cartesian velocity components. The array is updated every two minutes, resulting in the fourth dimension, time. Thus we have, essentially, blocks of data that represent every two minutes of the microburst phenomenon taking place.

Figure 2 illustrates the origin of the coordinate system used on the NCAR data tapes. The origin of the x,y,z coordinate system is located at CP-2. The x coordinate is measured positive toward the east; and the y coordinate is measured positive toward the north. The z coordinate is positive in the vertical direction upward. When implementing the wind data into the airplane equations of motion, one must be aware that the data are provided in an earth-fixed coordinate system.

At present, we have looked at three data sets. The primary data set we have looked at is the August 5 data set. It was measured in the region indicated in Figure 2. The numbers in parentheses are the x, y coordinates of the region in kilometers relative to CP-2. The June 29 data set also shown in Figure 2 is another data set that came out earlier. These data are not processed in exactly the same manner as the August 5 data and they may show more severe wind shear effects than are real. We want to caution you to not use this data set because all the smoothing techniques and mass balance verification procedures currently perfected by NCAR have not been applied to the June 29 data set. The July 14 data set was measured at the location indicated on Figure 2. A great deal of work with this data set has not yet been carried out. Never before have we measured velocity to the resolution achieved by JAWS in a volume of space that is, essentially, 12 km square and 2 km high. We have wind velocity entirely throughout this volume element. The data is provided to us on data tapes with an established grid system. The grid spacing for the August 5 case is 150 m in the horizontal direction (both lateral and longitudinal) and 250 m in the vertical direction (see Figure 3).

In the 12 km square by 2 km high volume element, there are 81 grid points on each side, plus 9 grid points in the vertical direction. One of the problems that scares everybody immediately when you look at this data set is that you have 81 by 81 by 9 grid points; and if you have three wind components at each grid point, you end up with approximately 177,000 data points. Storage capacity of a computer may thus begin to be

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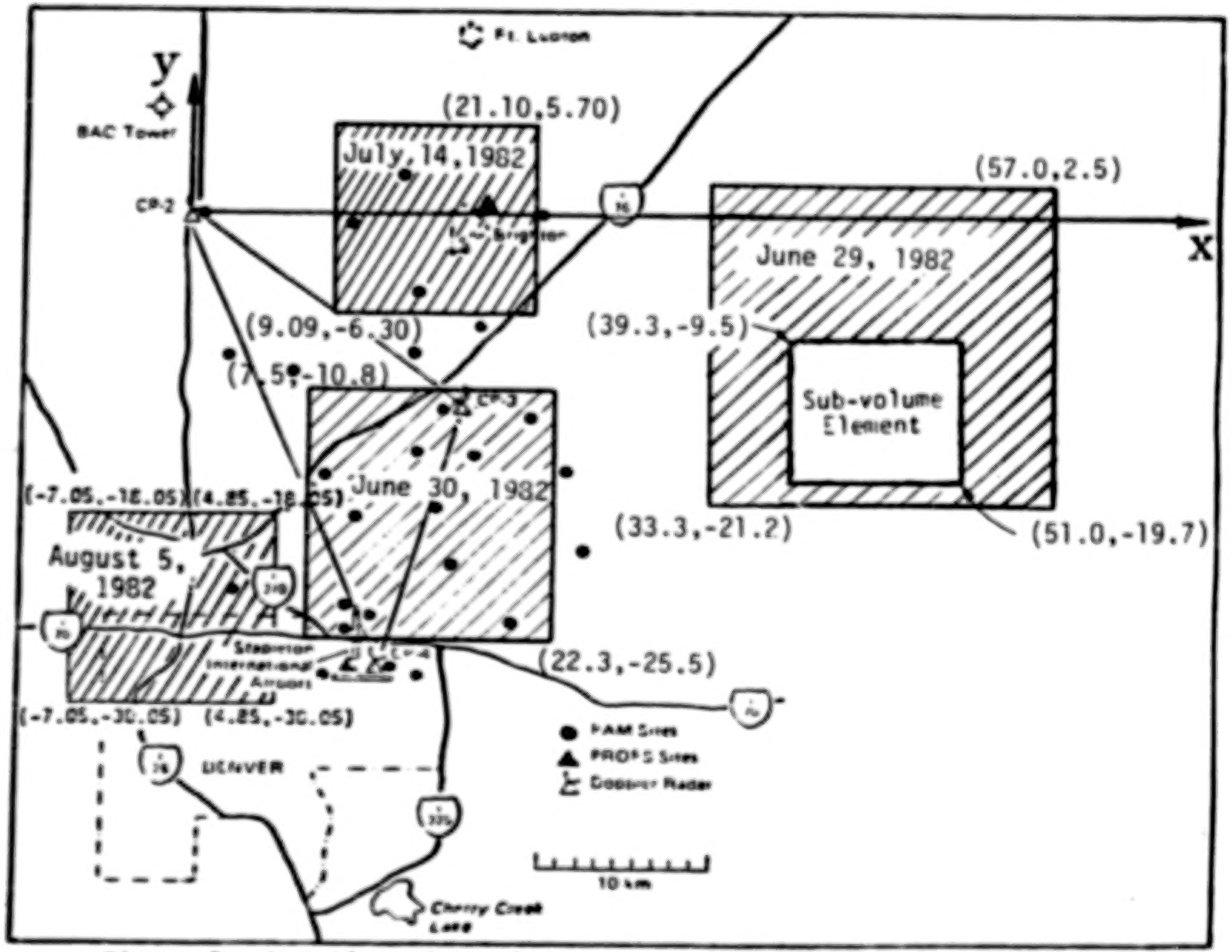
- Prepare from the JAWS data, four-dimensional computer models on microburst velocities as input for flight simulator models.

- Incorporate the new four-dimensional wind shear models into numerical computations to determine critical wind shear severity thresholds, access the scales of motion which lead to dangerous aircraft response, determine the relative importance of the horizontal versus the vertical wind speed component, define the test flight deterioration parameters, and evaluate operational procedures for use in wind shear encounters.

- Review flight simulator theories and aircraft equations of motion to assure compatibility of the wind shear models with existing simulator capabilities and computer storage capacity.

- Combine the instrumented aircraft high-frequency wind speed measurements with Doppler radar data to provide a meaningful turbulence model for addition to the wind shear simulation input models.

Figure 1. Objectives of current research



y
BAC Tower
CP-2
Ft. Lupton
(21.10,5.70)
July 14,1982
Brighton
x
(57.0,2.5)
June 29, 1982
(39.3,-9.5)
Sub-volume
Element
(51.0,-19.7)
(9.09,-6.30)
(7.5,-10.8)
CP-3
June 30, 1982
(33.3,-21.2)
(-7.05,-18.05)
(4.85,-18.05)
August 5,
1982
270
70
Stapleton
International
Airport
CP-4
(22.3,-25.5)
(-7.05,-30.05)
(4.85,-30.05)
25
DENVER
225
70
PAM Sites
PROFS Sites
Doppler Radar
10 km
Cherry Creek
Lake

Figure 2. Location of Doppler CP-2, CP-3, and CP-4. The origin of the XYZ coordinate is located at CP-2. The location of the August 5, 1982, and June 29, 1982, data sets are indicated by the shaded areas.

Split the big cube into eight sub-cubes through the point p. V1 through V8 are volumes of sub-cube which correspond to Node 1 through Node 8 located diagonally from the volume element. (Such as the shady volume V1 corresponds to Node 1.) If a1 through a8 are the wind speed values on corresponding nodes, then the value of wind speed at point p is:

$$W_p = \frac{\sum_{i=1}^{8} W_i v_i}{\sum_{i=1}^{8} v_i}$$

Total Number of Data Values
- = (81 x 81 x 9) x (3 wind components)
- = (59049) x (3 wind components)
- = 177147 data values

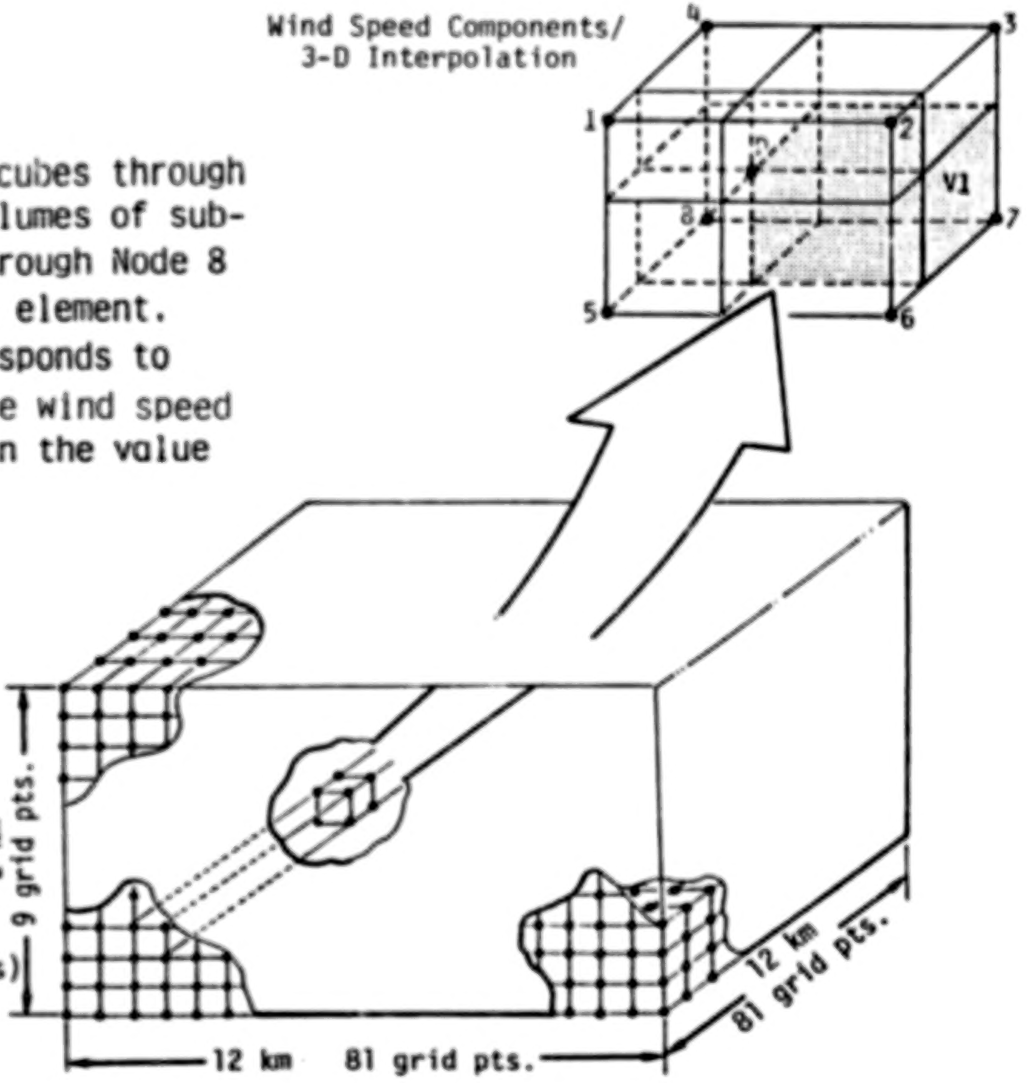

Wind Speed Components/
3-D Interpolation
1
2
3
4
5
6
7
8
p
V1
2 km
9 grid pts.
12 km
81 grid pts.
12 km
81 grid pts.

Figure 3. Handling the variable wind

a problem. However, I think this is not true for the NASA simulators. In turn, at FWG Associates we have had problems with our very small super micro-computer (40 kilobytes of storage) in storing that much data. Storage capacity on modern computers is not difficult to obtain. In the event that storage becomes a problem, we have selected volume elements of the data set, which I will describe to you in a moment.

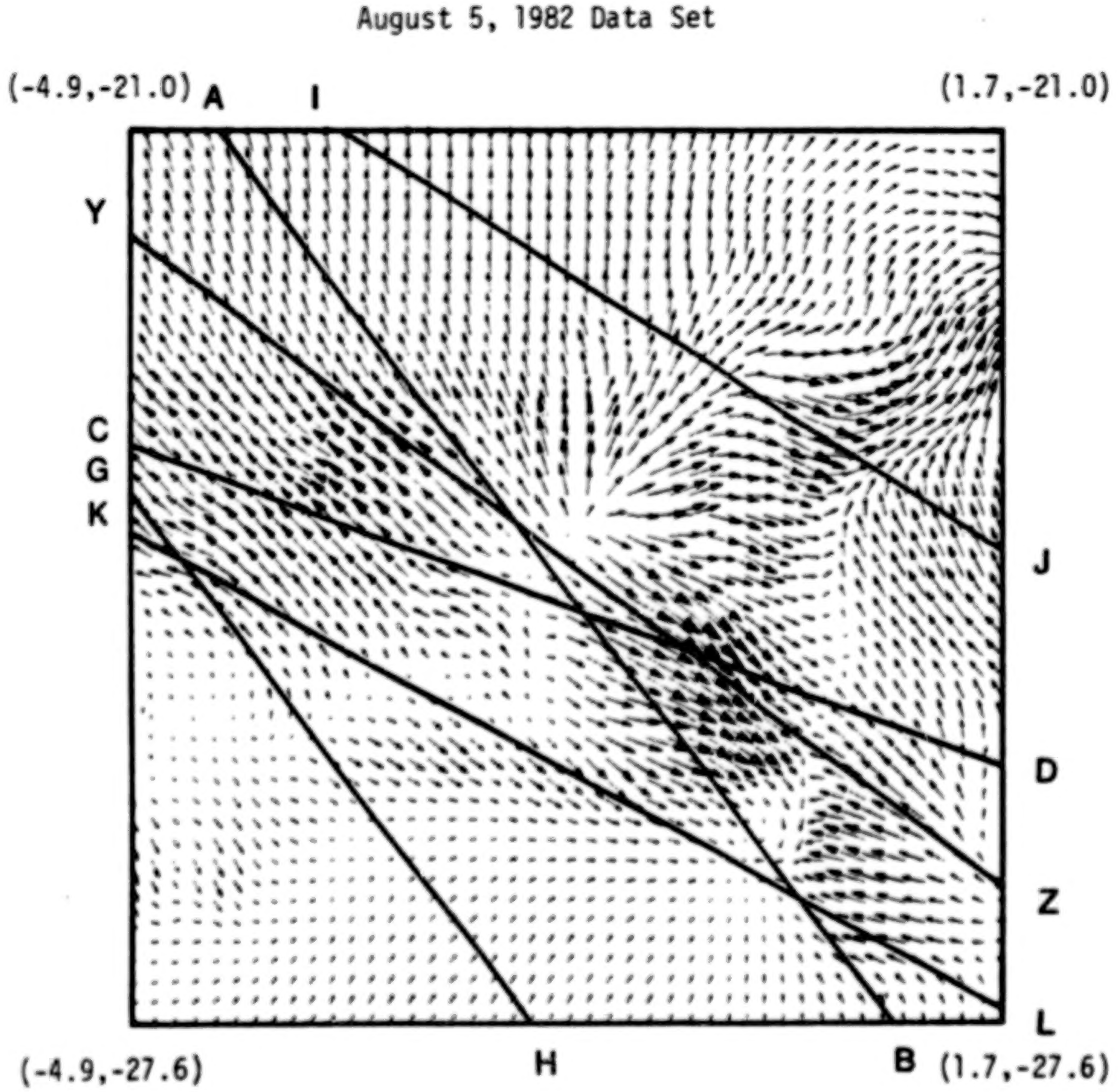
Recall that we are also talking about turbulence parameters for each grid station, such as turbulence intensities and length scales, if we can extract these from the radar signals. In turn, if you are interested in heavy rain, we can provide radar reflectivity. Thus, there may be as many as six parameters for each grid point. The storage capacity is thus doubled. The question of whether we can handle storage capacities of these magnitudes is one of the issues we want to discuss. Another problem which was identified was not so much storage as interpolation to find the wind speeds at the aircraft position at 64 times per second. This, I believe, is the typical rate for most simulators. The procedure we currently use is a volume weighting procedure as illustrated in Figure 3. If the airplane is at point p, we simply weight velocity at a neighboring grid point with the diagonally opposite sub-volume element. Thus, we interpolate the winds at the point and when the airplane moves to the next point, we repeat the interpolation. This would seem to take considerable time on a computer, but actually this represents only about eight or nine lines of computer programming, and is not difficult to do (see ref. 3). Moreover, NASA is doing it in real time on their simulator. Thus, I believe, handling this large amount of data is not difficult, and the urgent need for a simple analytical model everyone is talking about is not that pressing. I firmly believe that simply storing the full volume data set is the simplest model you can get. By the time you come up with a model that is representative of true microburst wind shear, it is just as easy to use realistic data that have been measured in the field.

Now let me address another issue which I hope will be discussed in detail. I feel it is very important to put the spatial derivatives or wind gradient into the aircraft equations of motion. There are nine spatial gradients of winds (Figure 4). These have never really been considered in previous analyses of aircraft motion, partly because we did not have the information available. I will show you later that the gradients do enter the analysis, and in some cases, we think can be very significant. Therefore, in addition to interpolating for the three wind speed components, you must also interpolate for the wind gradients when using JAWS data sets. Again, this interpolation is not excessively time consuming (ref. 3).

In order to assist you, the user of the JAWS data sets, we have identified paths through the full volume set along which wind shears occur. We have classified these as to severe, moderate, and light wind shear. The paths were initially selected by inspection. Figure 5 is a plot of the horizontal winds at ground level. The vectors indicate the direction of the wind and the size of the vector indicates the magnitude. The center of the microburst is clearly visible. We picked flight paths where a strong head wind changed to a strong tail wind along the path. If, for example, you fly through this data base, say along YZ, you have a strong head wind shifting to a tail wind. We picked a number of paths just by inspection. The path IJ was selected because it is interesting in that a relatively strong lateral wind shear occurs. Also, we selected some paths such as GH that we knew were relatively benign, but still challenging. We analyzed the particular wind field by conducting a computer simulation of aircraft performance along the respective paths. The aircraft was trimmed for a 3° approach along this flight path. Simple control law algorithms were used to maintain the approach path. The runway can be moved relative to the wind, or the wind relative to the runway, whichever way you like to look at it. A 3° approach along flight path AB, for example, with the runway at any position

$$\begin{bmatrix} \frac{\partial W_x}{\partial x} & \frac{\partial W_x}{\partial y} & \frac{\partial W_x}{\partial z} \\ \frac{\partial W_y}{\partial x} & \frac{\partial W_y}{\partial y} & \frac{\partial W_y}{\partial z} \\ \frac{\partial W_z}{\partial x} & \frac{\partial W_z}{\partial y} & \frac{\partial W_z}{\partial z} \end{bmatrix}$$

Figure 4. Wind vector gradients appear in the governing equations of motion for the aircraft (nine derivatives)



August 5, 1982 Data Set

JAWS Data Set Coordinates
in km Relative to CP2
(see ref. 4)

Scale
→ 40 kts

Figure 5. Flight paths overlaid on horizontal wind speed vectors

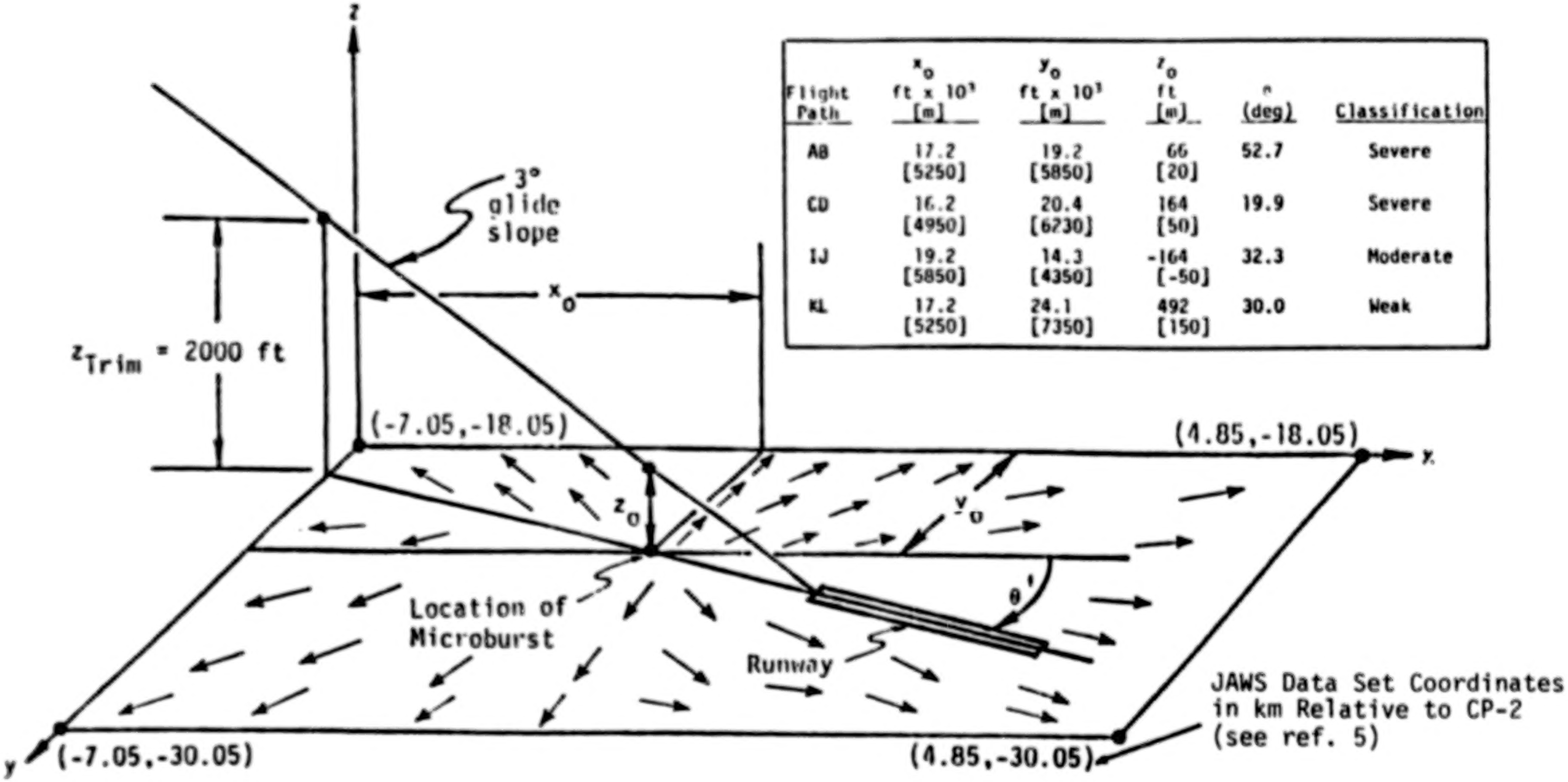
relative to where the center of the microburst is encountered can be simulated. We also simulated aircraft takeoff, with the position the aircraft flies through the microburst center again being adjusted. We ran several computer analyses and picked out what we classified as severe, moderate, and weak wind shear cases. The severe case on approach is one that our computer simulation, using relative simple control laws, was unable to fly; in other words, those cases in which the aircraft encountered the center of the microburst at a low altitude (roughly 100 m above the ground). In these cases, regardless of the fact that the control algorithm commands 15° to 20° pitch and full thrust to go-around, the aircraft could not fly and crashed; we called these cases moderate. We called those paths weak where a go-around was possible without too much difficulty, but where there was enough wind shear to make the control laws move around significantly.

A description of the paths and the nomenclature used to define them is shown in Figure 6. We trimmed the aircraft at roughly 2,000 ft. outside the data set. Then we picked some coordinates for each path which would represent the point at which the center of the microburst occurred. We measured those coordinates relative to the northwest corner of the data set. The coordinates of the NW corner shown on the figure are relative to CP-2. A new coordinate system for this specific data set is defined such that x_0 is the distance toward the east to the center of the microburst; y_0 is the distance toward the south to the center of the microburst, and z_0 is the height at which the airplane would pass through that microburst if it were able to maintain the 3° glide slope along the designated path. For example, taking line AB shown in Figure 5, the runway is oriented along this path and the aircraft is trimmed to make a 3° glide slope; x_0 and y_0 then indicate the position of the microburst center relative to the end of the runway, and z_0, which is a very critical parameter, is the height at which the airplane would pass through the microburst. The angle shown on Figure 6 is the angle of the path relative to the x_0 axis.

To reduce the magnitude of the data sets for the convenience of the user, we picked particluar flight paths, for example, path AB in Figure 5, and prepared sub-volume data sets called 1-, 2-, and 3-plane models. The sub-volume data sets were constructed by passing a vertical plane and two parallel planes on each side separated by 500 ft. through AB. Data from the full volume data set were then transformed to these data planes. The longitudinal velocity, w_x, relative to the plane is the wind speed component along the direction of the particular flight path (i.e., AB in this case), is the lateral wind which is perpendicular to x, and w_z is measured in the positive z direction upward.

The center of the microburst (or roughly the center) is the origin of the coordinate system. Figure 7 schematically illustrates how the data are tabulated on a corridor data set.

Figure 8 is a portion of a corridor data table for a 3-plane data set. A corridor along path AB is shown. The wind shear along this path is classified as severe, the origin is at the center of the microburst, the planes are separated by 500 ft. Plane 1 is 500 ft. to the side of the center plane and 3 is 500 ft. to the other side. Plane 2 runs directly down path AB (see Figure 5). The first column is the position along the path measured from the center of the microburst. The next three columns are the wind speed components in the x,y, and z direction, respectively. Notice that x is negative until the center of the microburst, i.e., x = 0. Then it is measured positive. To perform



z
3° glide slope
x_o
z_{Trim} = 2000 ft
(-7.05,-18.05)
(4.85,-18.05)
x
z_o
y_o
θ'
Location of Microburst
Runway
JAWS Data Set Coordinates in km Relative to CP-2 (see ref. 5)
y
(-7.05,-30.05)
(4.85,-30.05)

Flight Path	x_o ft x 10^3 [m]	y_o ft x 10^3 [m]	z_o ft [m]	θ' (deg)	Classification
AB	17.2 [5250]	19.2 [5850]	66 [20]	52.7	Severe
CD	16.2 [4950]	20.4 [6230]	164 [50]	19.9	Severe
IJ	19.2 [5850]	14.3 [4350]	-164 [-50]	32.3	Moderate
KL	17.2 [5250]	24.1 [7350]	492 [150]	30.0	Weak

Figure 6. Description of coordinate system and approach path orientation

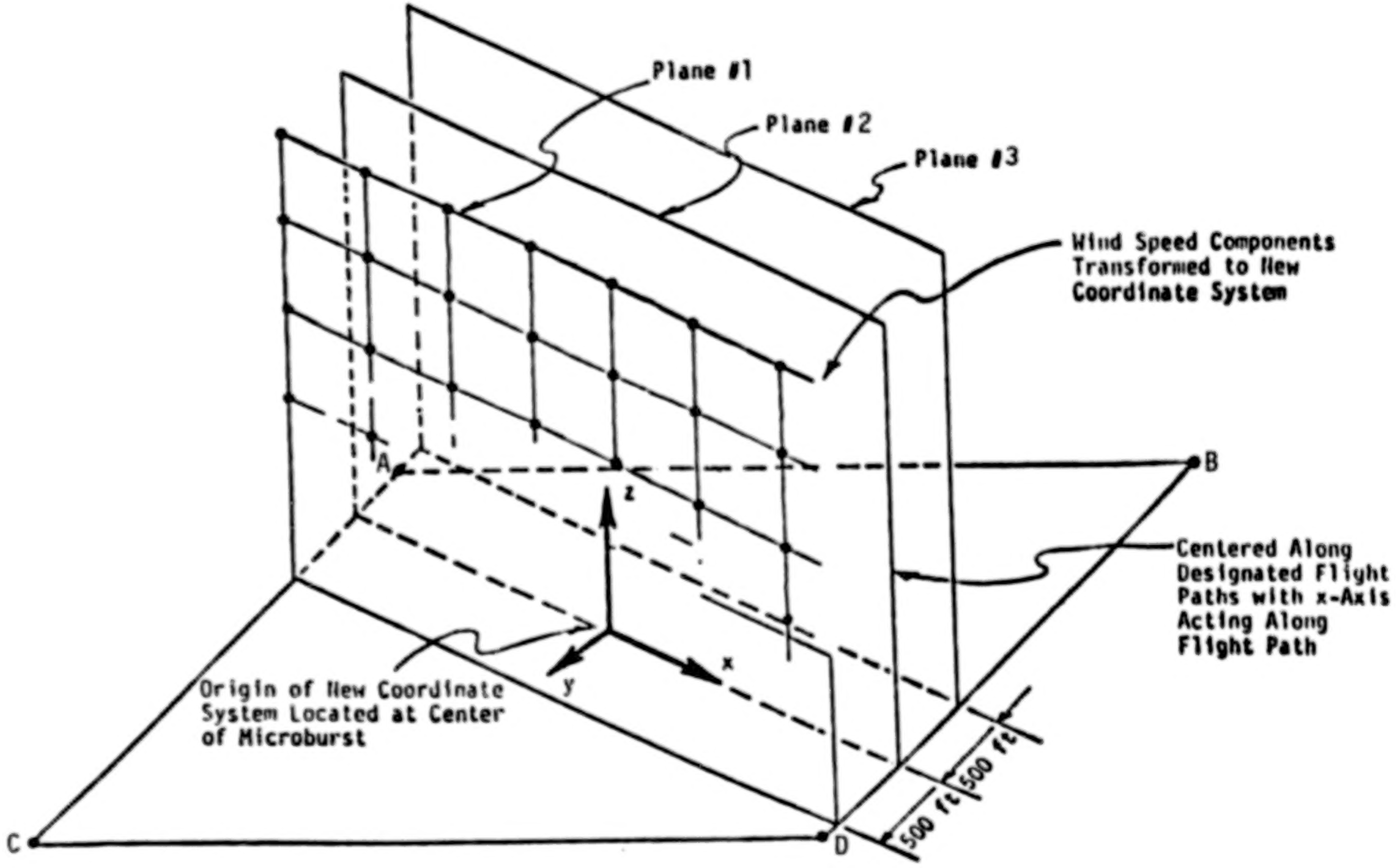

Plane #1
Plane #2
Plane #3
Wind Speed Components Transformed to New Coordinate System
A
B
z
Centered Along Designated Flight Paths with x-Axis Acting Along Flight Path
x
y
Origin of New Coordinate System Located at Center of Microburst
500 ft
500 ft
500 ft
C
D

Figure 7. Description of coordinate system and data planes

```
                    JAWS WIND FIELD #1
                 (Corridor Along Path AB)

          Profile Severity:  Severe
          Origin at Center of Microburst
          Planes Separated by 500 ft

                          Elevation:  0 ft AGL

             PLANE 1                  PLANE 2                  PLANE 3
     X       Wx      Wy      Wz       Wx      Wy      Wz       Wx      Wy      Wz
 -37500.     .00     .00     .00      .00     .00     .00      .00     .00     .00
 -37000.     .00     .00     .00      .00     .00     .00      .00     .00     .00
 -36500.     .00     .00     .00      .00     .00     .00      .00     .00     .00
 -36000.     .00     .00     .00      .00     .00     .00      .00     .00     .00
 -35500.     .00     .00     .00      .00     .00     .00      .00     .00     .00
 -35000.     .00     .00     .00      .00     .00     .00      .00     .00     .00
 -34500.     .00     .00     .00      .00     .00     .00      .00     .00     .00
 -34000.     .00     .00     .00      .00     .00     .00      .00     .00     .00
 -33500.     .00     .00     .00      .00     .00     .00      .00     .00     .00
 -33000.     .00     .00     .00      .00     .00     .00      .00     .00     .00
 -32500.     .00     .00     .00      .00     .00     .00      .00     .00     .00
 -32000.     .00     .00     .00      .00     .00     .00      .00     .00     .00
 -31500.     .00     .00     .00      .00     .00     .00      .00     .00     .00
 -31000.     .00     .00     .00      .00     .00     .00      .00     .00     .00
 -30500.     .00     .00     .00      .00     .00     .00      .00     .00     .00
 -30000.     .00     .00     .00      .00     .00     .00      .00     .00     .00
 -29500.     .00     .00     .00      .00     .00     .00      .00     .00     .00
 -29000.     .00     .00     .00      .00     .00     .00      .00     .00     .00
 -28500.     .00     .00     .00      .00     .00     .00      .00     .00     .00
 -28000.     .00     .00     .00      .00     .00     .00      .00     .00     .00
 -27500.     .00     .00     .00      .00     .00     .00      .00     .00     .00
 -27000.     .00     .00     .00      .00     .00     .00      .00     .00     .00
 -26500.     .00     .00     .00      .00     .00     .00      .00     .00     .00
 -26000.     .00     .00     .00      .00     .00     .00      .00     .00     .00
 -25500.     .00     .00     .00      .00     .00     .00      .00     .00     .00
 -25000.     .00     .00     .00      .00     .00     .00      .00     .00     .00
 -24500.     .00     .00     .00      .00     .00     .00    -7.72    2.60     .00
 -24000.     .00     .00     .00    -7.75    2.79     .00    -7.74    2.42     .00
 -23500.   -7.84    2.76     .00    -7.76    2.40     .00    -7.72    2.10     .00
 -23000.   -7.90    2.10     .00    -7.77    2.15     .00    -7.66    1.93     .00
 -22500.   -7.84    1.50     .00    -7.70    1.77     .00    -7.60    1.67     .00
 -22000.   -7.60    1.30     .00    -7.47    1.32     .00    -7.44    1.30     .00
 -21500.   -7.41    1.47     .00    -7.27    1.11     .00    -7.25     .81     .00
 -21000.   -7.34    1.87     .00    -7.22    1.29     .00    -7.36     .95     .00
 -20500.   -7.24    2.19     .00    -7.30    1.73     .00    -7.43    1.42     .00
 -20000.   -7.16    2.21     .00    -6.97    1.83     .00    -7.09    1.66     .00
 -19500.   -7.32    2.41     .00    -6.83    2.06     .00    -6.92    2.00     .00
 -19000.   -7.74    3.31     .00    -7.55    3.05     .00    -7.54    3.00     .00
 -18500.   -8.21    4.30     .00    -8.26    4.18     .00    -8.31    3.91     .00
 -18000.   -8.56    5.44     .00    -8.67    4.74     .00    -8.74    4.00     .00
 -17500.   -8.99    6.17     .00    -9.00    4.97     .00    -9.07    3.91     .00
 -17000.   -9.90    6.40     .00    -9.60    5.39     .00    -9.42    4.17     .00
 -16500.  -10.69    6.80     .00   -10.52    5.94     .00    -9.95    4.80     .00
 -16000.  -11.69    7.20     .00   -11.61    6.45     .00   -10.91    5.40     .00
 -15500.  -11.40    7.29     .00   -11.27    6.65     .00   -10.70    5.70     .00
 -15000.  -11.33    7.10     .00   -10.36    6.56     .00    -9.64    5.70     .00
 -14500.  -11.00    6.82     .00   -10.34    6.24     .00    -9.33    5.35     .00
 -14000.  -12.54    6.60     .00   -11.14    5.91     .00   -10.00    4.95     .00
 -13500.  -13.31    6.37     .00   -12.22    5.76     .00   -11.26    4.80     .00
 -13000.  -13.91    5.73     .00   -13.40    5.54     .00   -12.27    4.62     .00
 -12500.  -14.05    4.83     .00   -13.97    4.89     .00   -12.95    4.42     .00
 -12000.  -13.83    4.30     .00   -13.74    4.70     .00   -12.75    4.51     .00
 -11500.  -13.15    4.62     .00   -12.84    4.87     .00   -11.92    4.80     .00
 -11000.  -12.00    4.92     .00   -11.76    4.97     .00   -11.22    4.81     .00
 -10500.  -11.15    5.13     .00   -10.93    4.99     .00   -10.72    4.70     .00
 -10000.  -10.50    5.17     .00   -10.41    4.96     .00   -10.33    4.70     .00
  -9500.  -10.02    5.16     .00   -10.03    4.89     .00   -10.02    4.61     .00
  -9000.   -9.66    5.09     .00    -9.75    4.79     .00    -9.80    4.50     .00
  -8500.   -9.40    4.99     .00    -9.51    4.68     .00    -9.65    4.37     .00
  -8000.   -9.22    4.80     .00    -9.35    4.55     .00    -9.50    4.22     .00
```

W_x = longitudinal wind; W_y = lateral wind; W_z = vertical wind
x = horizontal distance

```
                       JAWS WIND FIELD #1 (continued)
                          (Corridor Along Path AB)
                            Elevation:  0 ft AGL
 -7500.   -9.14    4.76     .00    -9.32    4.41     .00    -9.60    4.02     .00
 -7000.   -9.14    4.61     .00    -9.42    4.22     .00    -9.75    3.80     .00
 -6500.   -9.24    4.43     .00    -9.64    4.00     .00   -10.04    3.53     .00
 -6000.   -9.40    4.23     .00    -9.92    3.75     .00   -10.43    3.24     .00
 -5500.   -9.83    4.02     .00   -10.31    3.49     .00   -10.97    2.90     .00
 -5000.  -10.33    3.82     .00   -10.93    3.22     .00   -11.71    2.53     .00
 -4500.  -10.95    3.62     .00   -11.70    2.93     .00   -12.79    2.14     .00
 -4000.  -11.90    3.45     .00   -13.14    2.63     .00   -14.30    1.73     .00
 -3500.  -13.21    3.27     .00   -14.92    2.32     .00   -15.09    1.21     .00
 -3000.  -14.25    2.98     .00   -15.67    1.90     .00   -15.71     .65     .00
 -2500.  -14.19    2.98     .00   -13.85    1.76     .00   -14.30     .38     .00
 -2000.  -15.65    4.17     .00   -13.25    2.11     .00   -12.08     .33     .00
 -1500.  -17.54    5.37     .00   -12.51    1.76     .00   -11.29    -.12     .00
 -1000.  -16.15    5.29     .00   -11.90    1.57     .00    -9.20    -.63     .00
  -500.  -15.42    5.40     .00   -11.80    1.74     .00    -9.95    -.03     .00
     0.  -12.65    4.66     .00   -11.67    1.10     .00    -9.45    -.17     .00
   500.   -4.24    3.23     .00    -4.23     .53     .00    -4.02    -.32     .00
  1000.    7.19    2.92     .00     4.50    1.14     .00     2.62     .50     .00
  1500.   13.40    3.79     .00    11.03    2.71     .00     8.33    2.11     .00
  2000.   17.74    5.25     .00    15.19    4.77     .00    12.55    4.60     .00
  2500.   22.02    7.91     .00    18.75    7.95     .00    15.05    7.06     .00
  3000.   27.12    9.74     .00    21.70   10.10     .00    17.60    8.51     .00
  3500.   30.67   10.04     .00    22.90    9.77     .00    18.51    8.30     .00
  4000.   27.83    9.11     .00    22.32    9.00     .00    18.59    7.77     .00
  4500.   25.39    8.12     .00    22.02    8.47     .00    19.70    7.92     .00
  5000.   25.31    8.19     .00    24.36    9.32     .00    21.29    9.86     .00
  5500.   24.10    9.13     .00    25.07   11.51     .00    22.30   12.22     .00
  6000.   23.06    9.93     .00    23.80   12.12     .00    21.67   12.99     .00
  6500.   22.81    9.10     .00    23.56   10.42     .00    21.24   10.99     .00
  7000.   22.12    7.35     .00    21.24    7.77     .00    18.76    7.29     .00
  7500.   17.35    5.26     .00    15.01    5.40     .00    13.06    5.19     .00
  8000.   11.22    3.06     .00     7.50    3.51     .00     8.04    3.59     .00
  8500.    6.85    1.42     .00     4.69    1.64     .00     4.27    1.83     .00
  9000.    5.13    -.53     .00     2.47    -.32     .00     1.31    -.09     .00
  9500.    3.70   -3.10     .00     2.10   -2.50     .00    -1.26   -2.49     .00
 10000.    1.60   -5.01     .00     1.06   -3.97     .00    -1.90   -3.54     .00
 10500.   -3.71   -6.00     .00    -1.85   -4.04     .00    -2.62   -2.90     .00
 11000.   -9.04   -8.30     .00    -5.66   -4.82     .00    -4.06   -2.43     .00
 11500.  -11.47   -9.00     .00    -7.50   -5.11     .00    -5.33   -2.55     .00
 12000.  -11.42   -8.52     .00    -8.21   -5.12     .00    -6.11   -2.55     .00
 12500.  -11.37   -8.79     .00    -8.66   -5.47     .00    -6.53   -2.50     .00
 13000.  -11.51   -9.64     .00    -9.13   -6.49     .00    -6.71   -2.41     .00
 13500.  -10.50   -8.57     .00    -8.35   -5.14     .00    -6.54   -1.93     .00
 14000.   -7.97   -4.59     .00    -6.75   -2.33     .00    -5.71    -.37     .00
 14500.   -5.80   -1.20     .00    -5.36    -.05     .00    -5.01     .81     .00
 15000.   -4.94     .47     .00    -4.67    1.13     .00    -4.49    1.74     .00
 15500.   -4.47    1.52     .00    -4.20    2.02     .00    -4.17    2.43     .00
 16000.   -4.20    2.29     .00    -4.11    2.64     .00    -4.00    2.95     .00
 16500.   -4.04    2.86     .00    -4.01    3.12     .00    -3.95    3.30     .00
 17000.   -3.94    3.25     .00    -3.94    3.50     .00    -3.93    3.73     .00
 17500.   -3.90    3.56     .00    -3.91    3.76     .00    -3.93    3.97     .00
 18000.   -3.90    3.80     .00    -3.91    3.95     .00    -3.92    4.11     .00
 18500.   -3.90    3.97     .00    -3.91    4.09     .00    -3.90    4.22     .00
 19000.   -3.89    4.12     .00    -3.89    4.22     .00    -3.87    4.34     .00
 19500.   -3.85    4.27     .00    -3.84    4.34     .00    -3.82    4.45     .00
 20000.   -3.75    4.43     .00    -3.76    4.49     .00    -3.75    4.58     .00
 20500.   -3.61    4.59     .00    -3.65    4.66     .00    -3.65    4.74     .00
 21000.   -3.49    4.77     .00    -3.47    4.86     .00    -3.49    4.94     .00
 21500.   -3.26    4.96     .00    -3.22    5.00     .00    -3.20    5.10     .00
 22000.   -2.82    5.17     .00    -2.76    5.36     .00    -2.70    5.44     .00
 22500.   -1.60    5.30     .00    -1.43    5.63     .00    -1.62    5.67     .00
 23000.     .16    5.34     .00      .29    5.84     .00     -.12    6.11     .00
 23500.     .63    5.17     .00      .94    6.23     .00     -.32    7.36     .00
 24000.    -.23    5.56     .00     -.74    6.76     .00    -2.32    8.44     .00
 24500.   -2.16    6.16     .00    -3.80    7.00     .00    -5.60    8.93     .00
 25000.   -3.53    6.70     .00    -5.56    7.35     .00      .00     .00     .00
 25500.   -3.58    6.82     .00      .00     .00     .00      .00     .00     .00
```

W_x = longitudinal wind; W_y = lateral wind; W_z = vertical wind
x = horizontal distance

Figure 8. Illustration of tabulated 3 planar data.

a simulation, the runway can be moved back and forth along the path and either takeoffs or landings can be simulated at any position relative to the center of the microburst

The important parameters, in terms of assuring that spatial wind shear is incorporated into the aircraft equations of motion, are $\dot{\alpha}$ and $\dot{\beta}$ and angular rotation. If the equations are written in the inertial coordinate system, then spatial derivatives appear in the equations of motion only in the aerodynamics coefficients (Figure 9), in the $\dot{\alpha}$ and $\dot{\beta}$ values, and in the angular rotations. Consider the $\dot{\alpha}$ and $\dot{\beta}$ terms as shown in Figure 10. Normally the derivative of alpha is taken to provide $\dot{\alpha}$ as shown in the figure. The values u and w are relative velocity values. Beta is handled similarly. To obtain the derivatives of the velocity, you write the equations in the body coordinate system and solve for $\dot{u}$ and $\dot{w}$ (see Figure 10). Notice that $\dot{u}$ and $\dot{w}$ contain spatial derivatives of the wind. Thus when computing $\dot{\alpha}$, the spatial derivatives automatically appear in your equations of motion. Remember that W_x, W_y, and W_z are given in earth coordinates and must be transformed to the body coordinates.

The spatial wind derivatives become even more important in their effect on rotations which appear in the aerodynamic coefficients (see Figure 9). For example, the lift coefficients, as aerodynamic derivatives with respect to p and q, are with respect to relative rotation. What is typically done in most systems of equations of motion is to solve for inertial values. Moment equations are typically formulated in an inertial coordinate system. What happens, however, is that the airplane is rotating relative to the earth (the normally computed rotation values), but the wind is also rotating (see Figure 11). The JAWS data show there is a lot of rotation in the wind (see Figure 12); therefore, the rotation of the wind must be subtracted from the inertial rotation of the airplane to get the relative rotation. The rotation of the wind comes directly from the nine derivatives, because angular rotation of the atmosphere is the anti-symmetric part of the tensor gradient (see Figure 13). The equations for the rotation of the aircraft relative to the airmass are given in Figure 13. The inertial values calculated from the moment equation are reduced by the angular rotation of the wind and appropriately transformed into the body coordinate system. These resulting values should be used to calculate the aerodynamic coefficients. We believe that these terms are fairly significant.

Details of the wind shear models are given in reference 5 and of the aircraft equations of motion in reference 6. Standardization of the procedure for implementing wind shear into simulators is imperative if meaningful training and exchange of results are to be achieved.

Lift Force:

$L = C_L \rho V^2 A/2$

$C_L = C_{L_0} + C_{L_\alpha}(\alpha) + C_{L_{\delta_E}}(\delta_E) + \frac{\bar{C}}{2V}(C_{L_q}(q) + C_{L_{\dot{\alpha}}}(\dot{\alpha}))$

$\quad + \text{ground effect}$

Drag Force:

$D = C_D \rho V^2 A/2$

$C_D = C_{D_0} + C_{D_\alpha}(\alpha) + C_{D_R}(\delta_R) + C_{D_\beta}(\beta) + \text{ground effect}$

where

C_{D_R} = drag coefficient due to rudder

C_{D_β} = drag coefficient due to side-slip

Moment:

$M = C_M \rho V^2 \bar{C}/2$

$C_M = C_{M_0} + C_{M_\alpha}(\alpha) + C_{M_{\delta_E}}(\delta_E) + \frac{\bar{C}}{2V}(C_{M_q}(q) + C_{M_{\dot{\alpha}}}(\dot{\alpha}))$

$\quad + C_{M_R}(\delta_R) + C_{M_\beta}(\beta) + \text{engine thrust effect}$

$\quad + \text{ground effect}$

where

C_{M_R} = change pitch due to rudder

C_{M_β} = change pitch due to side-slip

Figure 9. Lift, drag, and moment coefficients

$$\alpha = \frac{w}{u}\,; \quad \dot{\alpha} = \frac{u\dot{w} - w\dot{u}}{u^2 + w^2}$$

$$\beta = \frac{v}{V}\,; \quad \dot{\beta} = \frac{\dot{v}(u^2 + w^2) - v(u\dot{u} + w\dot{w})}{V^2\sqrt{u^2 + w^2}}$$

where

$$\dot{u} = \frac{X}{m} - g \sin\theta - \hat{W}_x - [q(w + W_z) - r(v + W_y)]$$

$$\dot{v} = \frac{Y}{m} + g \cos\theta \sin\phi - \hat{W}_y - [r(u + W_x) - p(w + W_z)]$$

$$\dot{w} = \frac{Z}{m} + g \cos\theta \cos\phi - \hat{W}_z - [p(v + W_y) - q(u + W_x)]$$

Figure 10. Derivatives of α and β in body coordinates

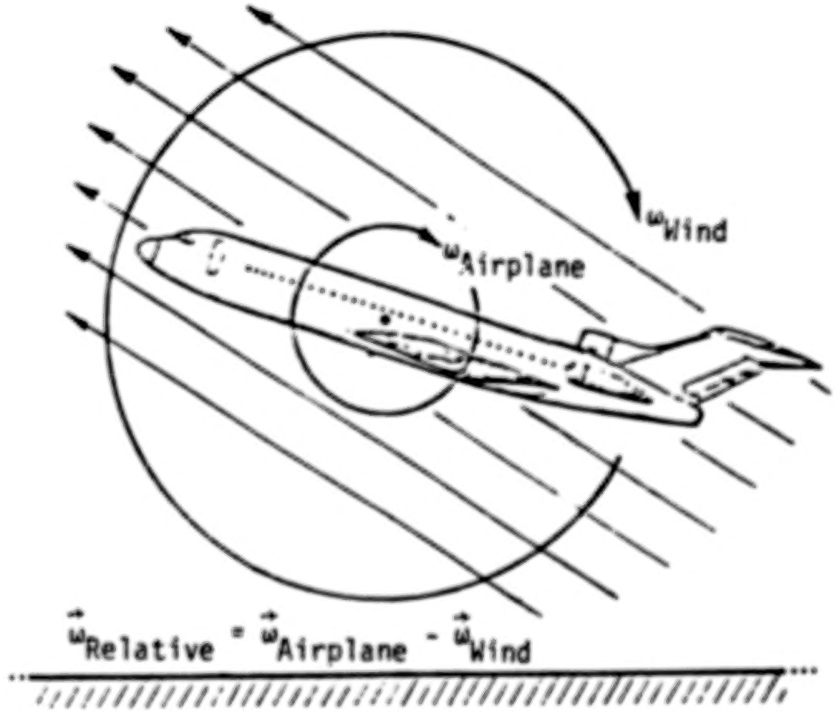

ω_{Wind}
$\omega_{Airplane}$
$\vec{\omega}_{Relative} = \vec{\omega}_{Airplane} - \vec{\omega}_{Wind}$

Figure 11. Schematic illustration of wind field rotation

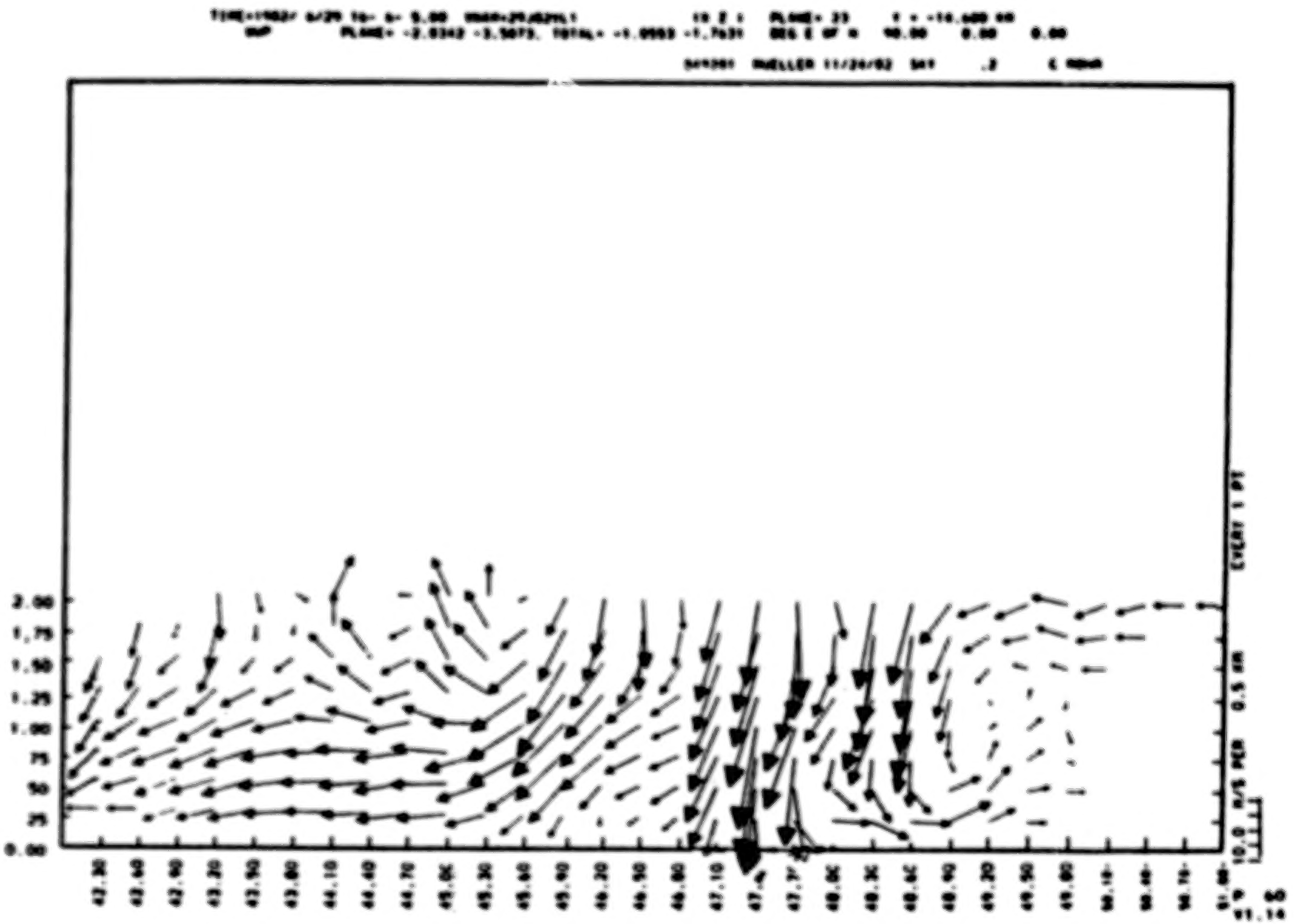


Figure 12. Shows rotation of wind field from JAWS data

- Relative angular rotation vector:

  $$\vec{\omega}_{rel} = \vec{\omega} - \vec{\omega}_W$$

- Angular rotation of atmosphere (antisymmetric part of tensor gradient $\vec{\nabla}\vec{W}$):

  $$\vec{\omega}_W = \frac{1}{2}\vec{\nabla} \times \vec{W}$$

  - Inertial coordinates:

    $$\vec{\omega}_W = \frac{1}{2}\left(\frac{\partial W_z}{\partial y} - \frac{\partial W_y}{\partial z}\right)_E \vec{i} + \frac{1}{2}\left(\frac{\partial W_x}{\partial z} - \frac{\partial W_z}{\partial x}\right)_E \vec{j} + \frac{1}{2}\left(\frac{\partial W_y}{\partial x} - \frac{\partial W_x}{\partial y}\right)_E \vec{k}$$

  - Body coordinates:

    $$\begin{pmatrix} p_{rel} \\ q_{rel} \\ r_{rel} \end{pmatrix} = \begin{pmatrix} p \\ q \\ r \end{pmatrix} - L_{BE} \begin{pmatrix} \left(\frac{\partial W_z}{\partial y} - \frac{\partial W_y}{\partial z}\right)_E \\ \left(\frac{\partial W_x}{\partial z} - \frac{\partial W_z}{\partial x}\right)_E \\ \left(\frac{\partial W_y}{\partial x} - \frac{\partial W_x}{\partial y}\right)_E \end{pmatrix}$$

Figure 13. Angular rotation relative to atmosphere

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WIND SHEAR AND TURBULENCE SIMULATION

Roland L. Bowles
Flight Management Branch
NASA Langley Research Center

The work conducted at NASA Langley in relation to simulation of wind shear is actually based on a broader effort. This effort is funded by the Simulation Technology Program at NASA Headquarters under the cognizance of the Human Factors Research and Technology Office. The Simulation Technology Program is a companion effort to the Langley Flight Management Program. There is no question that we, as an aviation community, are increasing our reliance on flight simulators. This is true both in pilot training and in research and development. In moving research concepts through the development pipeline, there is a sequence of events which take place (Figure 1): analysis, ground-based simulation, inflight simulation, and flight testing. Increasing fidelity as we progress toward the flight testing arena is accompanied by increasing cost. The question that seems to be posed here in relation to the meteorological aspects of flight simulation is, "How much fidelity is enough in this business, and can we quantify it?" As a part of the Langley Simulation Technology Program, we have three principal areas of focus, one being improved simulation of weather hazards. A close liaison with the JAWS project was established because of the Langley Simulation Technology interests regarding reliable simulation of severe convective weather phenomena and their impact on aviation systems.

Let me summarize what I believe is the current situation. There is no question that we have well-founded data collection programs under way. These are expensive programs and they are logistically difficult to conduct. They include Langley's severe storms effort, the JAWS effort, the Gust Gradient Program, and others. Under the term "others" is the work that is going on in heavy rain effects at Langley and the Icing Program at Lewis. The R&D systems development and pilot training community require the best available meteorological data. There is (as indicated by Figure 2) a gap between the data collection programs and implementation of these data into R&D and training simulators. There are a number of issues as shown in Figure 3 that are based on how we have conducted business in the past which have precluded optimum utilization of the atmospheric measurements derived from these large-field programs.

An approach to bridge the gap is straightforward (Figure 4). We need to identify the relevant data sources and develop models reflecting the best available data, interface those disturbance models with aerodynamics and flight management systems that are of interest to simulation activities, and conduct and publish well-established verification and evaluation results of the simulation process and research findings.

Simulation offers the only feasible approach for examining the utility of new technology and new procedures for coping with severe convective weather phenomena such as wind shear. Wind shear models currently employed in simulation studies, however, are very simple analytical forms, validation for which, with respect to either strength or structure, does not exist. Based on the premise that our confidence in safety-related studies, which necessarily

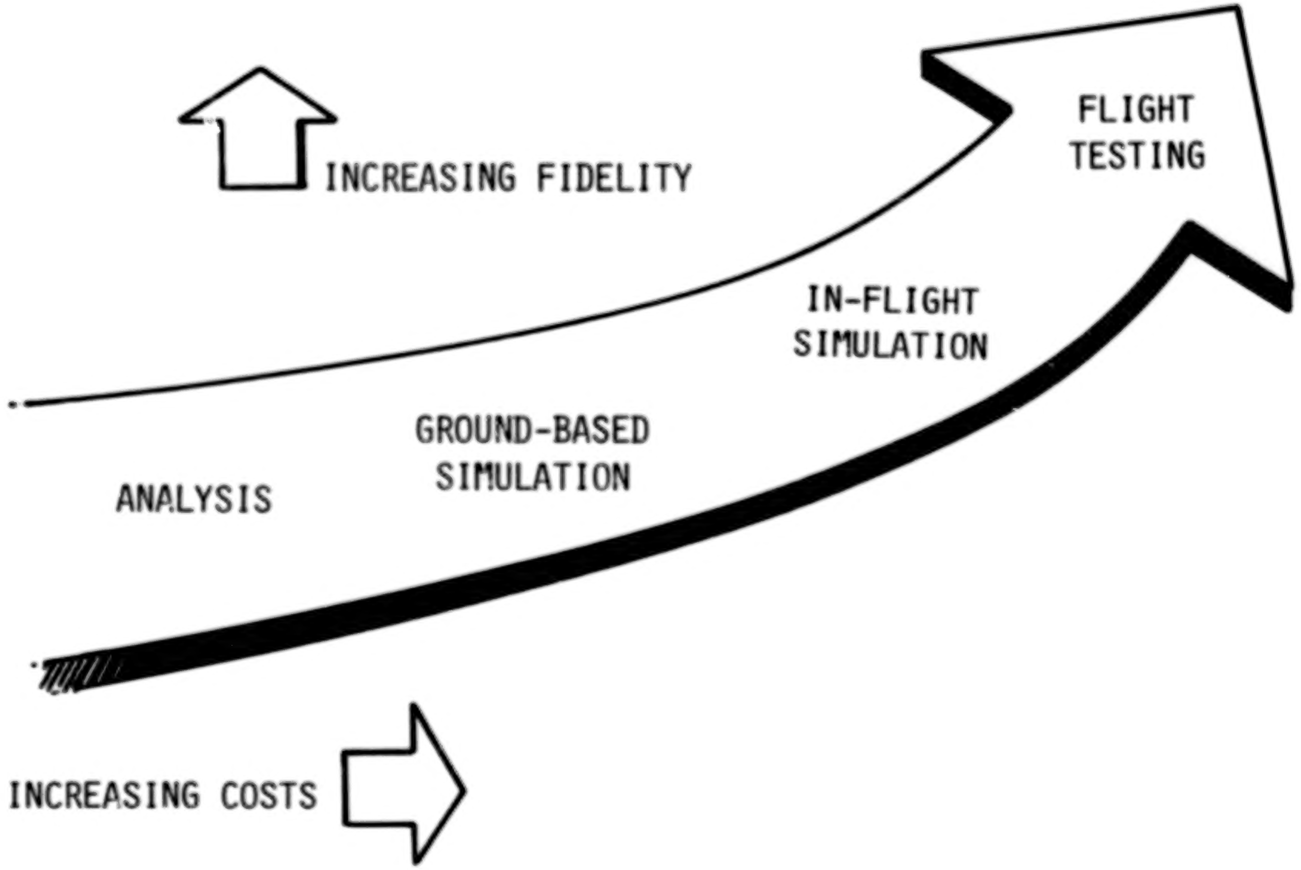
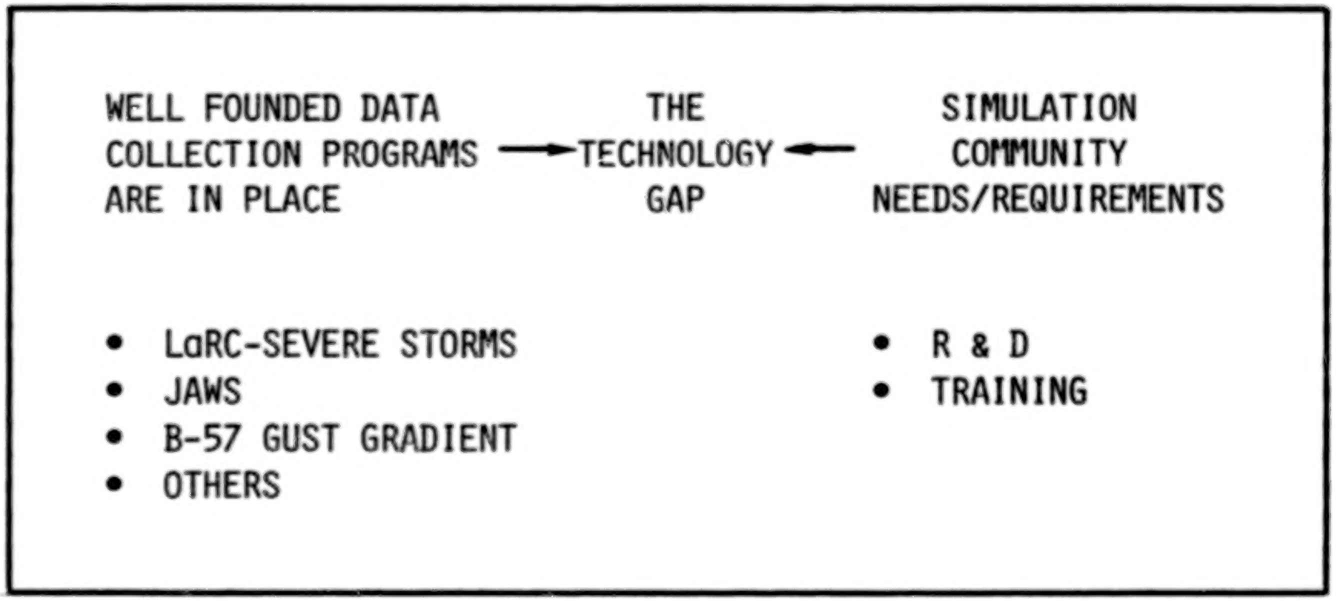

INCREASING FIDELITY
FLIGHT TESTING
IN-FLIGHT SIMULATION
GROUND-BASED SIMULATION
ANALYSIS
INCREASING COSTS

Figure 1. Hierarchy of design validation methods.



WELL FOUNDED DATA COLLECTION PROGRAMS ARE IN PLACE → THE TECHNOLOGY GAP ← SIMULATION COMMUNITY NEEDS/REQUIREMENTS

- LaRC-SEVERE STORMS
- JAWS
- B-57 GUST GRADIENT
- OTHERS

- R & D
- TRAINING

Figure 2. Weather hazard simulation current situation.

- INADEQUATE COMMUNICATIONS AND REQUIREMENTS DEFINITION
  - SIMULATION COMMUNITY
  - DATA COLLECTORS
- WIND SHEAR/TURBULENCE DATA BASE AND MODELS HAVE BEEN SPECIALIZED AND LIMITED
  - NON-UNIFORM WIND HAZARDS DATA BASE
  - AD HOC MODELS
  - LIMITED RESOLUTION
- SIMULATION DESIGN CRITERIA AND IMPLEMENTATION GUIDELINES ARE POORLY DEFINED
  - STANDARDS DO NOT EXIST
  - SELECTION CRITERIA FOR CANDIDATE DATA BASE AND DISTURBANCE MODELS NEED DEFINITION
  - INCONSISTENT TREATMENT OF WIND SHEAR/TURBULENCE EFFECTS ON AERODYNAMICS AND INTERFACE WITH EQUATIONS OF MOTION
  - MOTION/VISUAL FACTORS
- VAGUE SIMULATOR UTILIZATION STRATEGIES INVOLVING WEATHER HAZARDS
  - PERFORMANCE VERIFICATION AND VALIDATION
  - DOMAIN OF SIMULATION APPLICABILITY

Figure 3. The simulation gap.

- DATA SOURCES
- DISTURBANCE MODELS REFLECTING "BEST AVAILABLE" DATA
- INTERFACE DISTURBANCE MODELS WITH AERODYNAMICS AND FLIGHT MANAGEMENT SYSTEMS
- VERIFICATION AND EVALUATION

Figure 4. Key elements/approach.

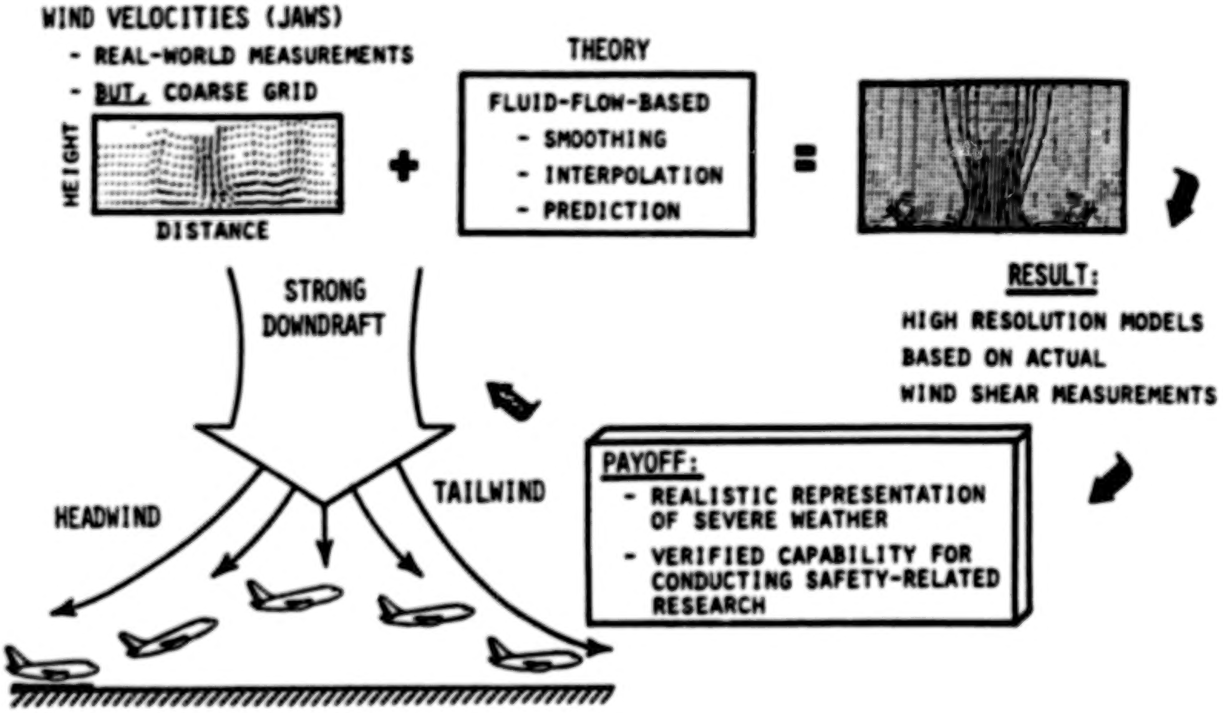
rely on these models, can be no better than our confidence in the validity of the models themselves, the criticality of this validation deficiency is clear. Fortunately, as a result of wind shear measurements recently provided from the JAWS Program (Joint Airport Weather Studies), the basic information required to correct this deficiency exists, but special techniques were required to implement the JAWS wind field measurements in simulation. For example, the JAWS data is taken with respect to a grid system that is very coarse when compared with aircraft dimensions. Also, because they are actual measurements, the data contains noise. In the present study (Figure 5), a technique using fluid-flow theory was developed to smooth and interpolate the JAWS measurements, providing a validated analysis model from which a wind shear data base can be generated and interfaced with real-time simulators.

Relative to modeling wind shear flow fields, I want to discuss some results of a computer generated microburst. This effort capitalizes on the fantastic developments that are occurring in computational fluid dynamics and related meteorological mathematical modeling. Langley is very fortunate to have a staff of seven computational meteorologists on site, and over the years they have put together a fairly sophisticated capability that deals with the synoptic scale coverage of U. S. continental weather. This model utilizes input from National Weather Service rawinsonde, surface, and satellite observations. The particular effort that we are currently pioneering is increased wind field resolution for a terminal area simulation. This is a computational-based numerical weather model (cloud scale) which can produce data bases that are not unlike the JAWS observations. Also, these data bases can be interfaced with simulators in the same manner as the JAWS data bases. For example, the cloud scale downburst model is initiated from observed temperature and humidity of Denver, 2300 GMT, June 30, 1982. Figure 6 depicts the time history of the downburst and the gust front evolution. The roll vortex forms immediately after the precipitation drops through the top boundary. It then propagates vertically downward, lagging the leading edge of the falling precipitation. Upon reaching the surface, the roll vortex propagates outward with the leading edge of the gust front. The most intense outflow speeds occur as the roll vortex reaches its lowest point and begins to propagate outwards (cf. Figure 6, Table 1). (The maximum radial outflow of 23.2 m/s occurs just before seven minutes). The gust front shape and slope vary as the outflow evolves. The "nose" (defined by the protruding edge of outflow which extends towards the warm air) becomes well defined after t = 8 min. The nose appears to be formed and maintained by the counter-clockwise circulation of the roll vortex. The forward edge of the outflow, defined as the "head", is produced as fast-moving outflow piles up behind the slower propagating gust front. The head contains the deepest region of cool outflow outside of the incipient precipitation area. Cool surface-layer flow toward the precipitation area, defined as "backflow", appears after t = 6 min. beneath the head. Backflow, as well as the head and nose structures of outflow, has been detected from actual measurements near gust fronts. The simulated outflow from the precipitation shaft does not remain undiluted. From the stream function field (Figure 6), entrainment of subsiding environmental air is apparent. Ambient air is first lifted several hundred meters as the cool outflow undercuts the warm environmental air. Then it sinks and some is entrained into the outflow layer. However, due to the dryness of ambient air in this experiment, the modest lifting is not enough to initiate condensation and the formation of a roll cloud above the head.

ADVANCED NUMERICAL WEATHER MODELS BASED ON FLUID-FLOW THEORETIC TECHNIQUES

PROBLEM:

LACK OF HIGH-FIDELITY WIND SHEAR MODEL FOR SAFETY-RELATED STUDIES OF A/C PERFORMANCE/CREW PROCEDURES/AVIONICS SYSTEM BENEFITS



WIND VELOCITIES (JAWS)
- REAL-WORLD MEASUREMENTS
- BUT, COARSE GRID

THEORY

FLUID-FLOW-BASED
- SMOOTHING
- INTERPOLATION
- PREDICTION

RESULT:

HIGH RESOLUTION MODELS
BASED ON ACTUAL
WIND SHEAR MEASUREMENTS

PAYOFF:
- REALISTIC REPRESENTATION OF SEVERE WEATHER
- VERIFIED CAPABILITY FOR CONDUCTING SAFETY-RELATED RESEARCH

Figure 5.- Methodology for wind shear modeling.

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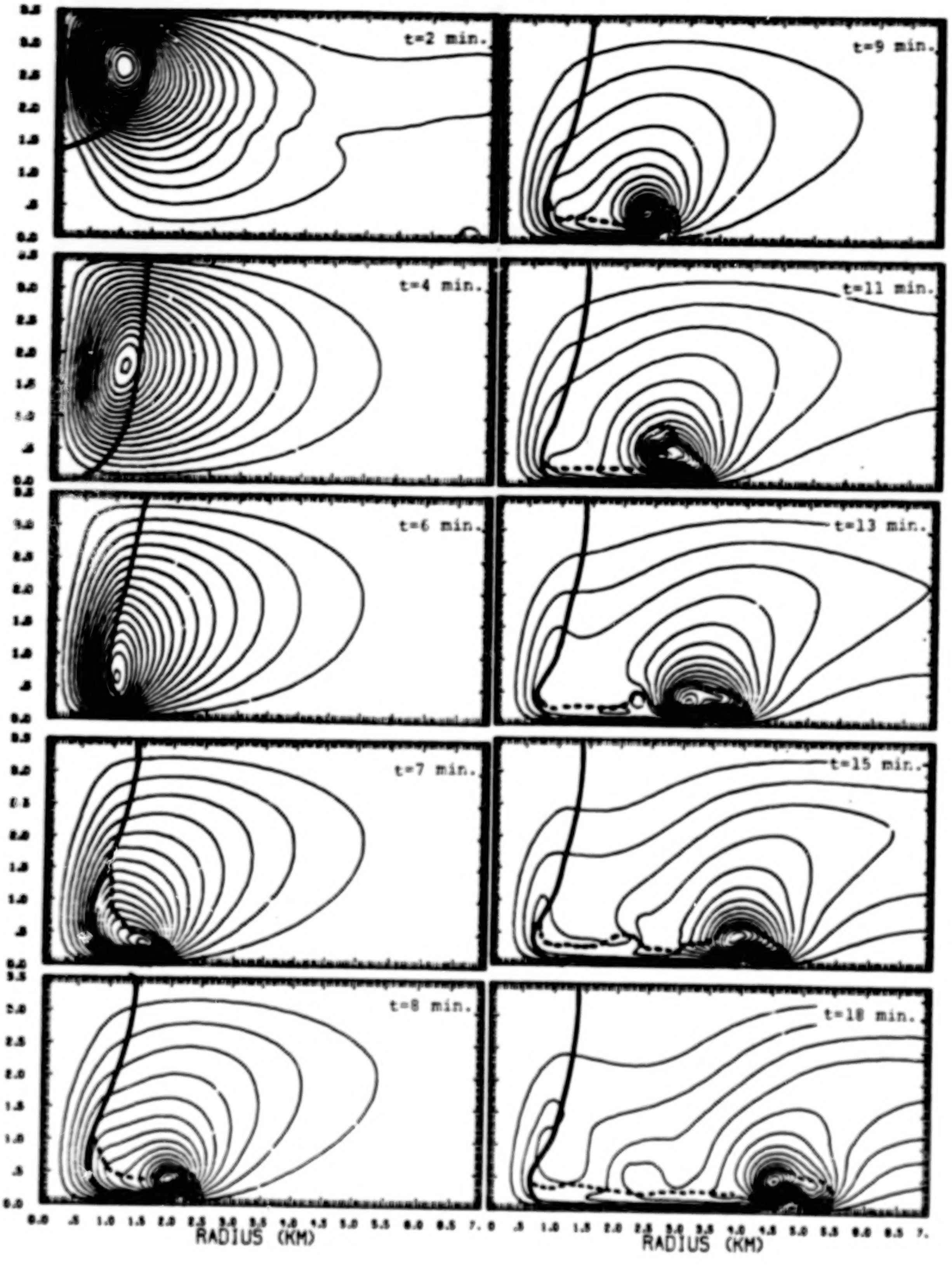


Figure 6. Time history of a simulated downburst.

Time (min)	Maximum outflow speed (m/s)	Maximum downdraft speed (m/s)
2	0.3	2.2
4	1.7	10.3
6	21.6	16.1
7	21.9	14.9
8	19.9	13.9
9	16.5	14.1
11	16.6	15.0
13	17.7	16.0
15	17.9	16.5
18	17.2	16.5

Table 1 Maximum outflow and downdraft speeds as a function of time for the 2300 GMT 30 June 1982, Denver simulation.

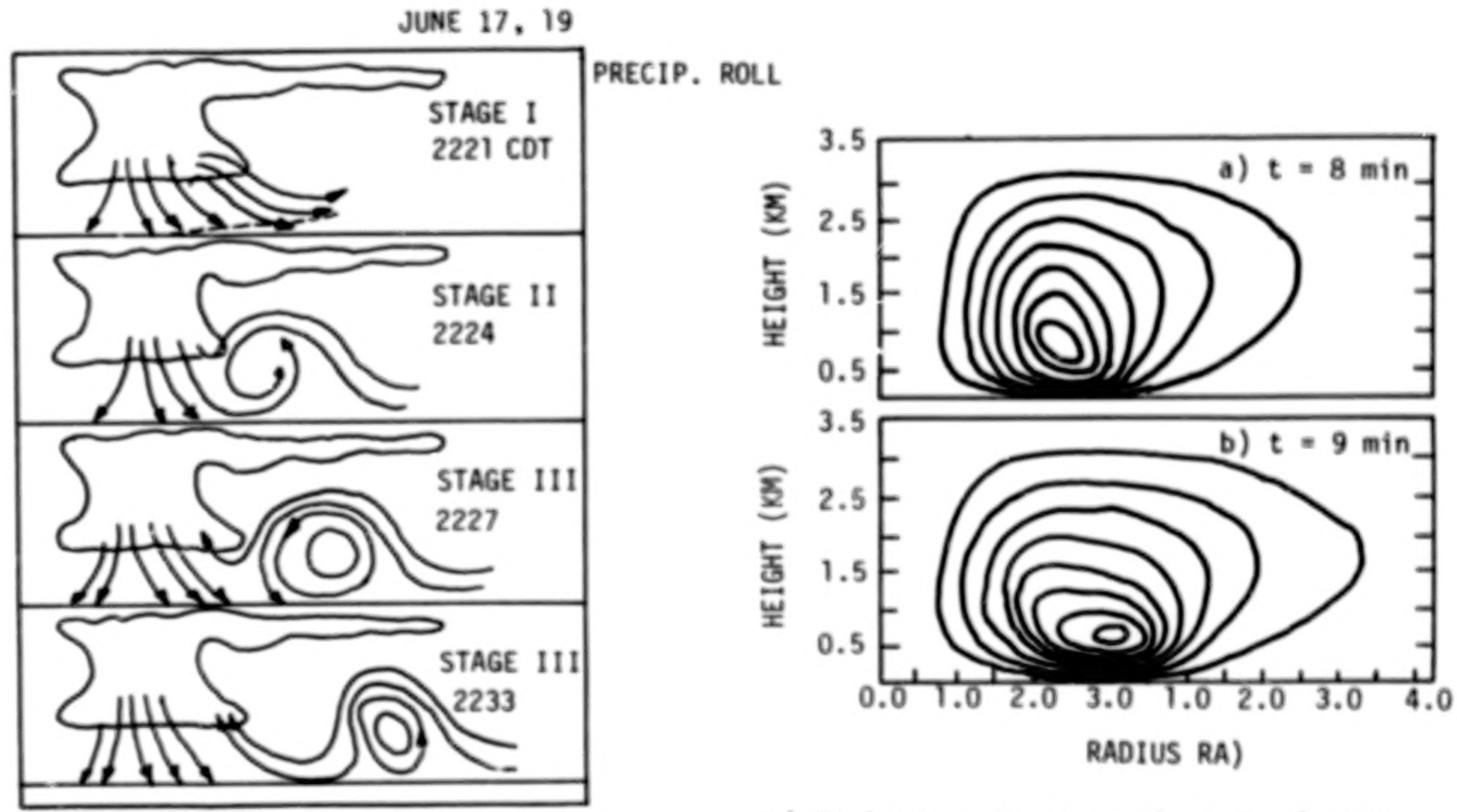
For the particular case study represented in Figure 6, the maximum outflow and downdraft speeds as a function of time are listed in Table 1. The computations were achieved with a 2-D axisymmetric Navier-Stokes model with the Z axis as the axis of symmetry. The maximum observed outflow speed was 21.9 m/s which translates to approximately 42 knots differential across the core of the microburst. Differentials of this magnitude and attendant downdraft speeds were observed during the JAWS program.

Figure 7 illustrates a comparison of classical (Ref. 1) gust front formation with computed results. Using Doppler radar, Wakimoto has observed a reflectivity pattern of precipitation, defined as a precipitation roll, which revolves in a horizontal roll near the gust front (Figure 7a). This feature is simulated by using the 2315 GMT 4 June 1973 Norman, Oklahoma, sounding as initial data for temperature and humidity. The computed stream function and radar reflectivity are shown at t = 8 min and t = 9 min (Figure 7b). The precipitation roll forms as the roll vortex moves radially outward from the precipitation shaft. Strong low-level outflow (> 20 m/s) sweeps rain out of the precipitation shaft and around the center of the roll vortex. Rain trapped in the roll vortex circulation eventually evaporates or falls to the ground. The lifetime of the simulated precipitation roll was only a few minutes, and its structure was very similar to the larger and more persistent precipitation roll observed by Wakimoto (cf. Figure 6a).

Figure 8 represents a vertical cross-section of the velocity field for the computer microburst initialized from June 30, 1982, soundings. As can be seen, the vortex rolls are well formed at t = 9 min. The vortex rolls represent complex and intense flows and may have significant impact on large airplanes operating close to ground beyond that of the classical microburst phenomena involving downdraft and divergent outflow.

The computer output shown in Figure 8 provides a wind shear data base on a uniform grid mesh of 30 m. resolution. This data base plus an interpolation technique is easily interfaced with real-time piloted simulators and provides what I would consider as a simple wind shear model. I do not suggest that we calculate, in real time, the complex fluid flow equations which give rise to microburst phenomena. To the contrary, we can generate high resolution wind shear data bases off-line and easily interface them with piloted simulators.

Figure 9 outlines three principal elements one must consider when developing wind shear models for application in the aviation context. First is the characterization of environment itself; technical issues remain to be addressed with regard to both wind shear severity and structure. The ad hoc committee, in my view, has not done a good job in responding to what the community has been trying to tell us regarding these issues. For example, consider the wind shear threat selection critieria. Frost (Ref. 2) has explained a rationale for selecting interesting wind shear profiles from the JAWS August 5 microburst event; I more or less filtered and studied the same cases. However, one JAWS data base provides an infinity of wind shear profiles and we have examined very few to date. Inherent classification of the wind shear environment, whether it is stochastic or deterministic, requires some thought. Is differential outflow ΔV characterization enough, or do we need probability of exceedance? Relative significance of vertical and horizontal scales of atmospheric motion is another area which requires careful consideration as well as pressure and temperature variations.


JUNE 17, 19
PRECIP. ROLL
STAGE I
2221 CDT
STAGE II
2224
STAGE III
2227
STAGE III
2233
a) t = 8 min
b) t = 9 min
HEIGHT (KM)
3.5
2.5
1.5
0.5
0.0
1.0
2.0
3.0
4.0
RADIUS RA)

a) Wakimoto's conceptual model of the evolution of a gust front and precipitation roll.

b) Field distributions of stream function (dashed lines) and radar reflectivity (solid lines) of a simulated downburst and precipitation roll at (a) t = 8 min., and (b) t = 9 min.

Figure 7. Comparison of classical gust front formation with computed results .

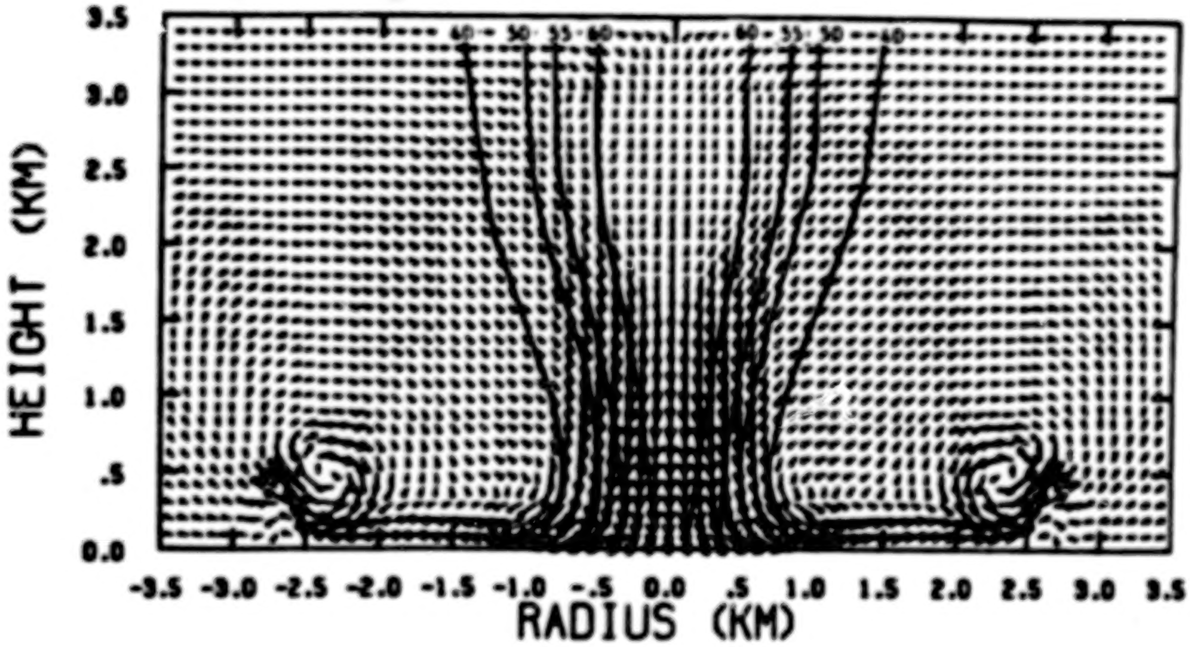


Figure 8.- Vector field of wind velocity at t = 9 min.

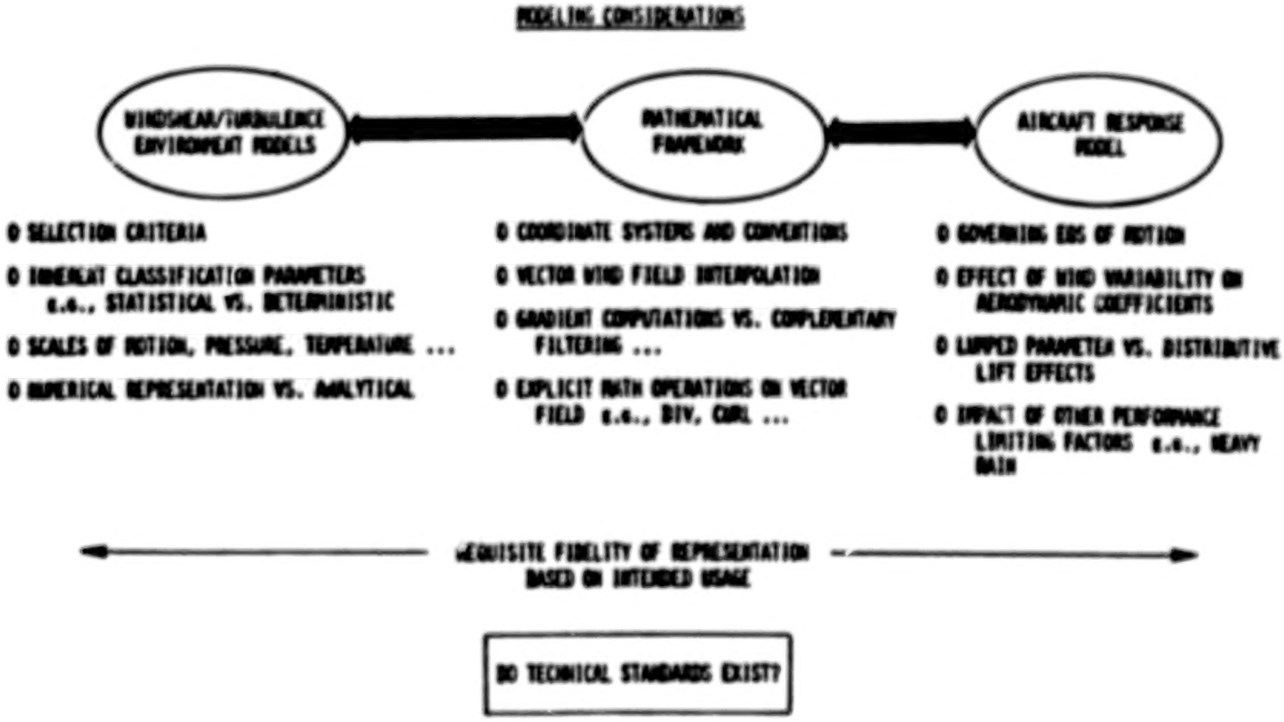

MODELING CONSIDERATIONS
WINDSHEAR/TURBULENCE ENVIRONMENT MODELS
MATHEMATICAL FRAMEWORK
AIRCRAFT RESPONSE MODEL
O SELECTION CRITERIA
O INHERENT CLASSIFICATION PARAMETERS e.g., STATISTICAL VS. DETERMINISTIC
O SCALES OF MOTION, PRESSURE, TEMPERATURE ...
O NUMERICAL REPRESENTATION VS. ANALYTICAL
O COORDINATE SYSTEMS AND CONVENTIONS
O VECTOR WIND FIELD INTERPOLATION
O GRADIENT COMPUTATIONS VS. COMPLEMENTARY FILTERING ...
O EXPLICIT MATH OPERATIONS ON VECTOR FIELD e.g., DIV, CURL ...
O GOVERNING EQS OF MOTION
O EFFECT OF WIND VARIABILITY ON AERODYNAMIC COEFFICIENTS
O LUMPED PARAMETER VS. DISTRIBUTIVE LIFT EFFECTS
O IMPACT OF OTHER PERFORMANCE LIMITING FACTORS e.g., HEAVY RAIN
REQUISITE FIDELITY OF REPRESENTATION BASED ON INTENDED USAGE
DO TECHNICAL STANDARDS EXIST?

Figure 9.- Modeling considerations.

Secondly, a consistent mathematical framework and vector wind field interpolation technique are required for implementing the JAWS data into simulators. There is no question that in terms of simulator utilization, simple wind shear models are attractive. Given the x, y, z position of the aircraft an algebraic evaluation of f_1, f_2, f_3 to give three wind components is a desired property as long as the model represents the wind shear phenomena being studied. I would also point out that a numerical data base combined with an appropriate mathematical structure can also constitute a "simple" wind shear model. The third area considered in Figure 9 is the aircraft response model. The proper integration of the wind shear environment with the simulated vehicle aerodynamics is an important part of the problem. If we can specify technical standards regarding meteorological aspects of wind shear models, the aircraft response and performance impact has to reflect that environment with reasonable levels of fidelity.

Figures 10 and 11 summarize the current situation regarding wind shear and turbulence simulation capability resident at the Langley Research Center. At the present time, we have implemented all three of the volumetric data sets produced by the JAWS project, i.e., June 29, July 14, and August 5, in addition to the simplified two- and three-plane corridor data. We found that a trivial amount of computer resource is required to implement the corridor data sets; in fact, they can be implemented at less cost than the current FAA specified SRI wind shear models.

Operational flexibility for application of the JAWS data is an issue which can be easily handled. For example, we locate the data centroid of the volumetric wind field relative to any crucial point on the runway, either GPIP or threshold, so that the data base can be moved at will relative to the runway. We also establish an arbitrary rotation of the data base about the centroid thus providing different wind shear profiles for given approach or take off flight path.

In addition to the JAWS data base, we also provide the 21 SRI/FAA profiles and a variety of turbulence models which probably are not adequate for their intended purpose. The overall operational philosophy, as illustrated in Figure 11, allows us to interface any number of flight simulators in our real-time simulation complex with any specific wind shear environment. For example, some aircraft performance results that I will shortly present were obtained using the TSRV simulator which is based on 737-100 model. However, a number of other simulators reflecting different levels of flight management systems sophistication could have been used. The bottom line is that we can make a landing approach through the August 5 JAWS data followed by an approach through the SRI Kennedy data within the time it takes to push the buttons and read data from disks.

The question of interfacing an arbitrary vector wind field with airplane flight and aerodynamic characteristics is important to the validity of the overall simulation process. Typically, the simulator development community is required to interface new wind shear environments with an existing simulator, the development of which required large investments of both manpower and dollars. Simulators which reflect complex flight management systems are evolutionary developments occurring over many years and we do not wish to let wind shear be the "tail that wags the dog." Generally a new wind shear environment, such as JAWS, must be retrofit into an already available

CURRENT WINDSHEAR/TURBULENCE SIMULATION CAPABILITY

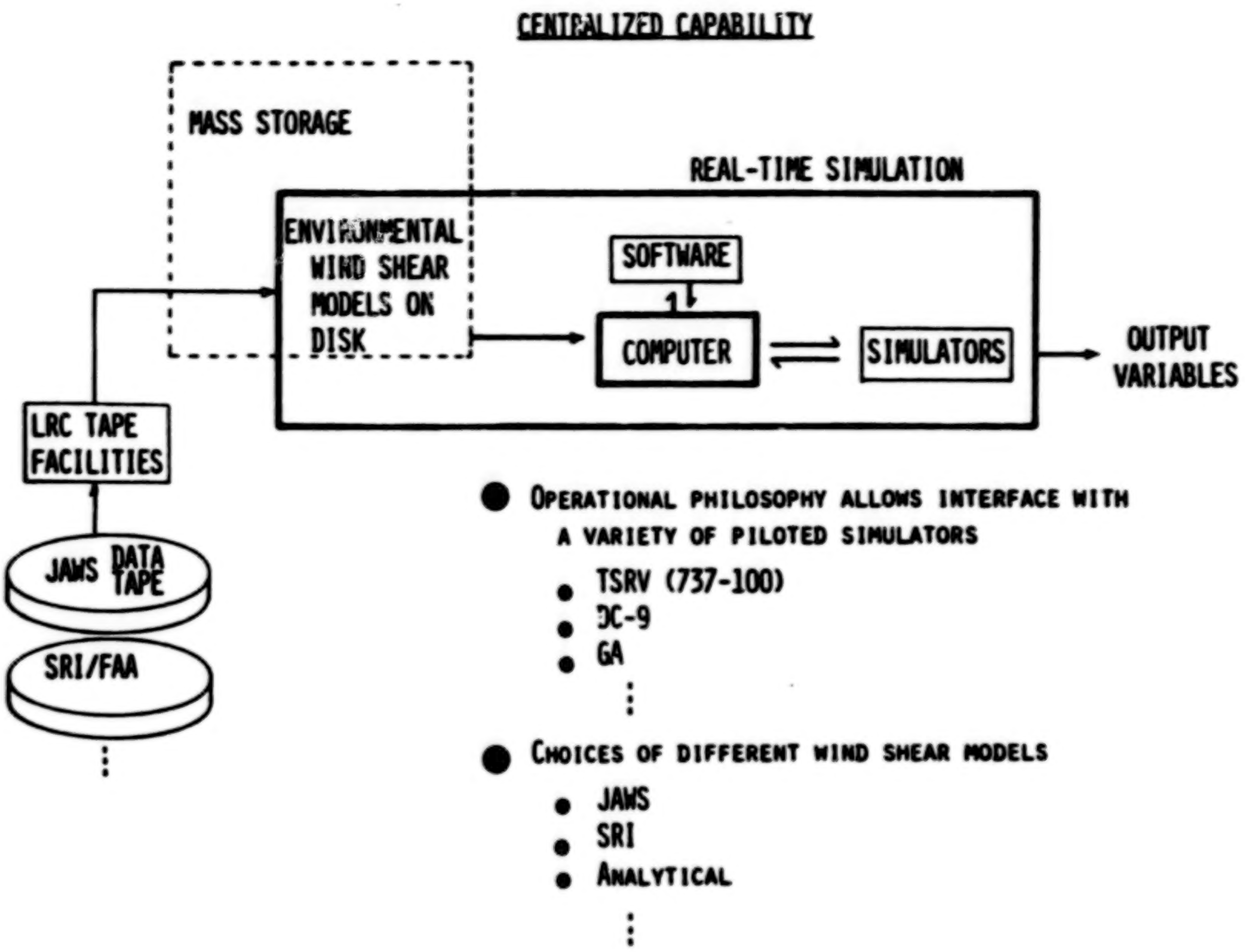
WINDSHEAR DATA BASE

- JAWS VOLUMETRIC WIND FIELDS
    - JUNE 29
    - JULY 14
    - AUGUST 5
- SIMPLIFIED TWO AND THREE PLANE REPRESENTATIONS OF AUGUST 5 CASE
- APPLICATION FLEXIBILITY
    - USER SELECTED SUBDOMAIN
    - ARBITRARY LOCATION OF DATA CENTROID RELATIVE TO GPIP
    - ARBITRARY ORIENTATION OF DATA VOLUME RELATIVE TO RUNWAY
    - WIND FIELD SCALING PRESERVES MASS FLOW CONTINUITY
- 21 SRI/FAA PROFILES
    - ACCIDENT RECONSTRUCTIONS
    - TOWER DATA
    - THEORETICAL MODELS

TURBULENCE MODELS/DATA BASE

- STANDARD MIL. SPEC. (MIL-F-87851B)
- SRI/FAA CHARACTERIZATION
- NASA DEVELOPED NON-GAUSSIAN

Figure 10.- Current wind shear simulation capability.


CENTRALIZED CAPABILITY
MASS STORAGE
REAL-TIME SIMULATION
ENVIRONMENTAL WIND SHEAR MODELS ON DISK
SOFTWARE
COMPUTER
SIMULATORS
OUTPUT VARIABLES
LRC TAPE FACILITIES
JAWS DATA TAPE
SRI/FAA

- Operational philosophy allows interface with a variety of piloted simulators
  - TSRV (737-100)
  - DC-9
  - GA
  - ⋮
- Choices of different wind shear models
  - JAWS
  - SRI
  - Analytical
  - ⋮

Figure 11.- Current wind shear philosophy.

simulator and aerodynamic model which presumably have proven flight characteristics in still air. The salient features of this retrofit process, as applied to the Langley Research Center simulator, are outlined in Figure 12. As seen in Figure 12, the key baseline assumptions are that the aircraft is rigid with a plane of symmmetry as well as a "point approximation" for the aerodynamic model. Engine characteristics are also assumed known. The lump parameter aerodynamic model assumes uniform wind over the aircraft and the usual treatment of quasi-steady aerodynamics. Since aerodynamic forces acting on aeroplanes do not respond instantaneously to changes in angle of attack and sideslip these effects are approximated based on conventional wisdom which is thought to be adequate for rigid airplanes in still air. In implementing the JAWS wind shear, we assumed a 3-D frozen field. The vector wind field is interpolated using a tri-linear technique which provides the three-axis mean winds within a cube whose vertex points are defined by the eight closest data mesh points. The nine partial derivatives (spatial wind gradients) of the wind field are determined as a no-cost byproduct of the interpolation technique.

It is interesting that the FAA AC-120-41 advisory circular (Ref. 3) now calls for output data that provide the partial derivatives as part of the evaluation plan. As a matter of fact, for the first time ever, JAWS has given us the ability to compute all nine spatial wind gradients. This was not possible before with the SRI wind shear models.

For the direct aerodynamic interface, we relax the uniform wind assumption over the airplane. The assumption is made that the scales of atmospheric motion in the JAWS data base are large enough relative to span and cord lengths that the flow can be treated as linearly distributed. The three-axis velocity components and their x, y, z spatial gradients are evaluated at mass center in real time. This calculation is done at whatever iteration rate required to satisfy the dynamics of the process. They are, however, evaluated along the trajectory of the mass center. Thus, we compute them only where they are needed to interface with the aerodynamics. Quasi-steady aerodynamics are directly computed in terms of these spatial wind gradients and the rotational effects discussed by Frost and Bowles (Ref. 4) are incorporated in the force and moment calculations.

In general, knowledge of both wind field and its gradient matrix is required to support aerodynamic calculations if the linear field approximation is used (see Figure 12). The above discussion implies that wind shear effects enter directly in the feedback loops of vehicle force and moment equations. We currently model the velocity and accelerations of the aircraft relative to the air mass with components taken in body axes. With the state vector chosen in this manner the integrals of the force and moment equations directly support the necessary aerodynamic calculations. The nine spatial derivatives are used to compute quasi-steady aerodynamics and the rotational effects produced by span and streamwise wind shear variations.

I will now describe a simulator experiment and present results based on simulated flight in the JAWS August 5 volumetric data base. Actually, Langley implemented the June 29 microburst data a year ago and demonstrated it to the National Research Council Wind Shear Study Committee. Several of the Aircraft Performance Committee members had the opportunity to fly in a microburst environment for the first time. The individuals who were exposed to the

VECTOR WIND FIELD INTERFACE WITH FLIGHT DYNAMICS

BASE LINE ASSUMPTIONS

- AIRCRAFT IS RIGID WITH PLANE OF SYMMETRY
- "POINT APPROXIMATION" FOR AERODYNAMICS
  - UNIFORM WIND OVER A/C
  - QUASI-STEADY AERO

SIMULATOR IMPLEMENTATION TECHNIQUES

- 3D-FROZEN FIELD
- TRI-LINEAR INTERPOLATION OF VECTOR WIND FIELD
  - LAGRANGE POLYNOMIAL BASIS FUNCTIONS
  - NINE PARTIAL DERIVATIVES PROVIDED AS A NO COST BY-PRODUCT
  - METHOD EASILY GENERALIZED TO 4-D INTERPOLATION
- LINEAR FIELD APPROXIMATION
  - SCALES OF ATMOSPHERIC MOTION SUCH THAT WIND IS, AT MOST, LINEARLY DISTRIBUTED OVER A/C
  - X,Y,Z GRADIENTS OF 3-COMPONENT VELOCITIES AND THEIR VALUES AT MASS CENTER
  - QUASI-STEADY AERO EFFECTS DEPEND ON SPATIAL WIND GRADIENTS
  - ROTATIONAL EFFECTS PRODUCED BY SPAN AND STREAMWISE SPATIAL GRADIENTS INCLUDED IN FORCE AND MOMENT CALCULATIONS (GENERATED BY WIND FIELD VORTICITY)
- GENERAL CASE IMPLEMENTATION OF WIND SHEAR DEPENDS ON

$$\begin{bmatrix} u_x & u_y & u_z \\ v_x & v_y & v_z \\ w_x & w_y & w_z \end{bmatrix} \quad \text{AND } \bar{V}_w(x,y,z) = (u,v,w)^T$$

Figure 12.- Wind shear interface with simulated flight and aerodynamic characteristics.

simulator experience provided strong comment on their perception of the wind shear hazard and its potential impact on aviation safety.

The specific simulator test conditions for the August 5 wind shear penetration experiment are given in Figure 13. This particular simulator replicates the advanced flight management systems and crew interfaces incorporated in the Transport Systems Research Vehicle (TSRV) operated by the Langley Research Center. The flight and propulsion characteristics are those of a B737-100. This simulator has attributes which provides a nice environment in which to evaluate wind shear characteristics; i.e., electronic displays, panel mounted controllers, and sophisticated flight control augmentation. The autoland is inertially smoothed and the velocity vector control wheel steering mode provides good flying qualities for precision flight path management. The advanced primary flight display provides both airspeed and groundspeed information as well as inertial flight path angle and potential flight angle.

Twelve approach paths were preselected because of their interesting windshear properties and both autoland and manual approaches were flown. The simulator experiment evaluation criteria are shown in Figure 14. The evaluation criteria were based on FAA advisory circulars AC-120-29 (Ref. 5) and AC-20-57A (Ref. 6). Based on these selected sources, quantitative results were obtained for 100 ft. decision height CAT II approach criteria, acceptable touchdown performance and dispersion. Qualitative information was collected on whether the pilots would have aborted the approach and why, and pilot commentary regarding windshear severity rating was also obtained. For the twelve selected paths, the autoland was not disengaged so that 100 ft. decision height and touchdown data could be obtained and compared with certification criteria. Figures 15 and 16 illustrate graphically the longitudinal and lateral touchdown criteria, on a two sigma basis, for application to CAT II flight director and autoland certification.

Figures 17 and 18 illustrate the autoland 100 ft. decision height performance for the twelve selected paths in the JAWS August 5 windshear environment. Figure 17 also shows the decision height performance for a manual approach for path AB 2 using velocity vector control wheel steering, and Figure 18 shows that the manual approach for path PQ 12 was aborted at an altitude of 180 ft. Although the touchdown was successful for the manual approach for path AB 2, the airspeed dropped to 98 kts. and the pilot experienced an angle of attack warning and stick shaker. The current decision height window shown on Figures 17 and 18 is bounded by a ±12 ft. linear glide slope deviation at 100 ft. altitude, which is about one dot on a flight director, and ±5 kts. from V-reference. The decision height window is designed in such a way as to assure a successful landing under wind shear conditions up to 8 kt./100 ft. from 100 ft. altitude to the ground.

A literal interpretation of Ref. 5 suggests a lateral decision height window, at 100 ft. altitude, of the type shown in Figure 19. The window requirement of Figure 19 stems from the fact that at 100 ft. of altitude the airplane should be positioned so that the cockpit is within the lateral confines of the runway and the airplane is tracking so as to remain within the lateral confines of the runway. For the airplane to be within the lateral confines of the runway means a +75 ft. maximum localizer deviation for a standard 150 ft. wide runway. Tracking to remain within the lateral confines

- FLIGHT PARAMETERS
  - APPROACH CONFIGURATION
  - 85,000 LBS G.W. AND .2 CG
  - 125 KT V REF
  - -3° GLIDESLOPE
- ENVIRONMENTAL FACTORS
  - 10,000 FT RUNWAY
  - 750 FT BREAKOUT, 10,000 FT RVR
  - 6 KT HEADWIND REPORT, NO TURBULENCE
  - PILOTS WARNED OF WIND SHEAR IN THE SECTOR
- CONTROL MODES
  - INERTIALLY SMOOTHED AUTOLAND
  - ADVANCED VV-CWS
- ADVANCED PRIMARY FLIGHT DISPLAY
  - INERTIAL FLIGHT PATH ANGLE
  - GROUND SPEED

Figure 13.- Simulator test conditions for JAWS August 5 wind shear penetration experiment.

- SELECTED SOURCES
    - AC 120-29
    - AC 20-57A

- QUANTITATIVE
    - 100 FT DECISION HEIGHT CAT II APPROACH CRITERIA
    - ACCEPTABLE TOUCHDOWN PERFORMANCE

- QUALITATIVE
    - PILOT COMMENTARY AND WIND SHEAR SEVERITY RATING
    - OTHER OBSERVATIONS

Figure 14.- Evaluation criteria for JAWS August 5 wind shear penetration experiment.

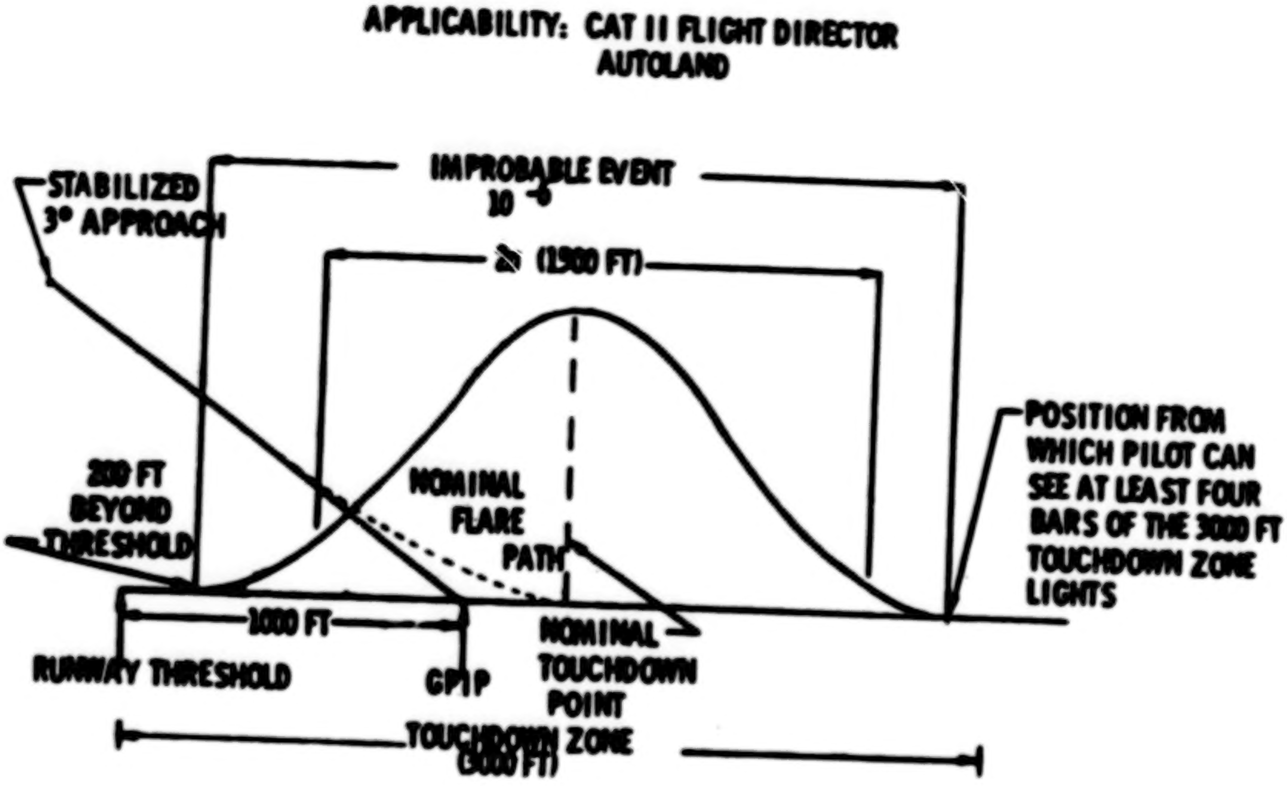

APPLICABILITY: CAT II FLIGHT DIRECTOR
AUTOLAND
STABILIZED
3° APPROACH
IMPROBABLE EVENT
10^-6
2σ (1900 FT)
200 FT
BEYOND
THRESHOLD
NOMINAL
FLARE
PATH
POSITION FROM
WHICH PILOT CAN
SEE AT LEAST FOUR
BARS OF THE 3000 FT
TOUCHDOWN ZONE
LIGHTS
1000 FT
RUNWAY THRESHOLD
GPIP
NOMINAL
TOUCHDOWN
POINT
TOUCHDOWN ZONE
(3000 FT)

Figure 15.- Longitudinal dispersion certification requirement.

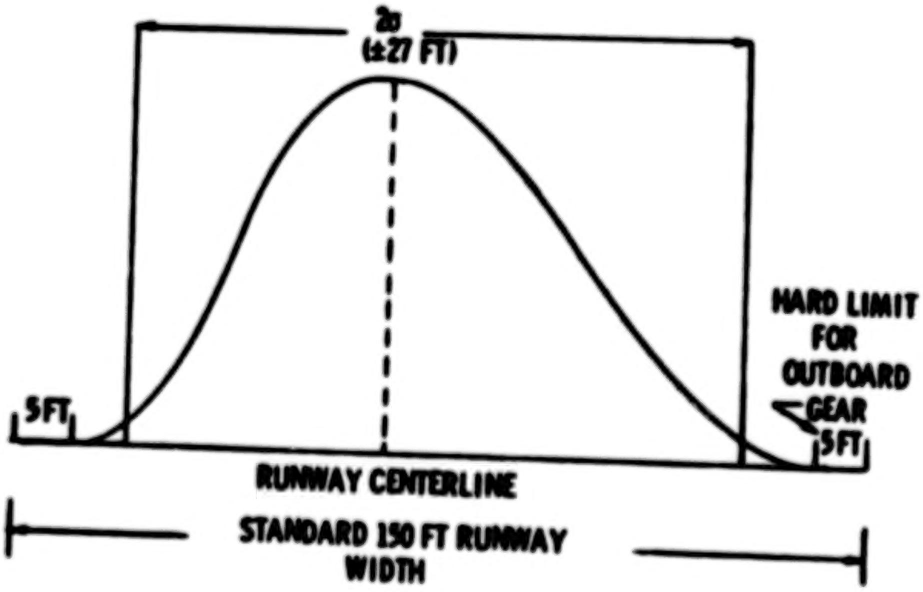

2σ
(±27 FT)
5 FT
HARD LIMIT
FOR
OUTBOARD
GEAR
5 FT
RUNWAY CENTERLINE
STANDARD 150 FT RUNWAY
WIDTH

Figure 16.- Lateral dispersion certification requirement.

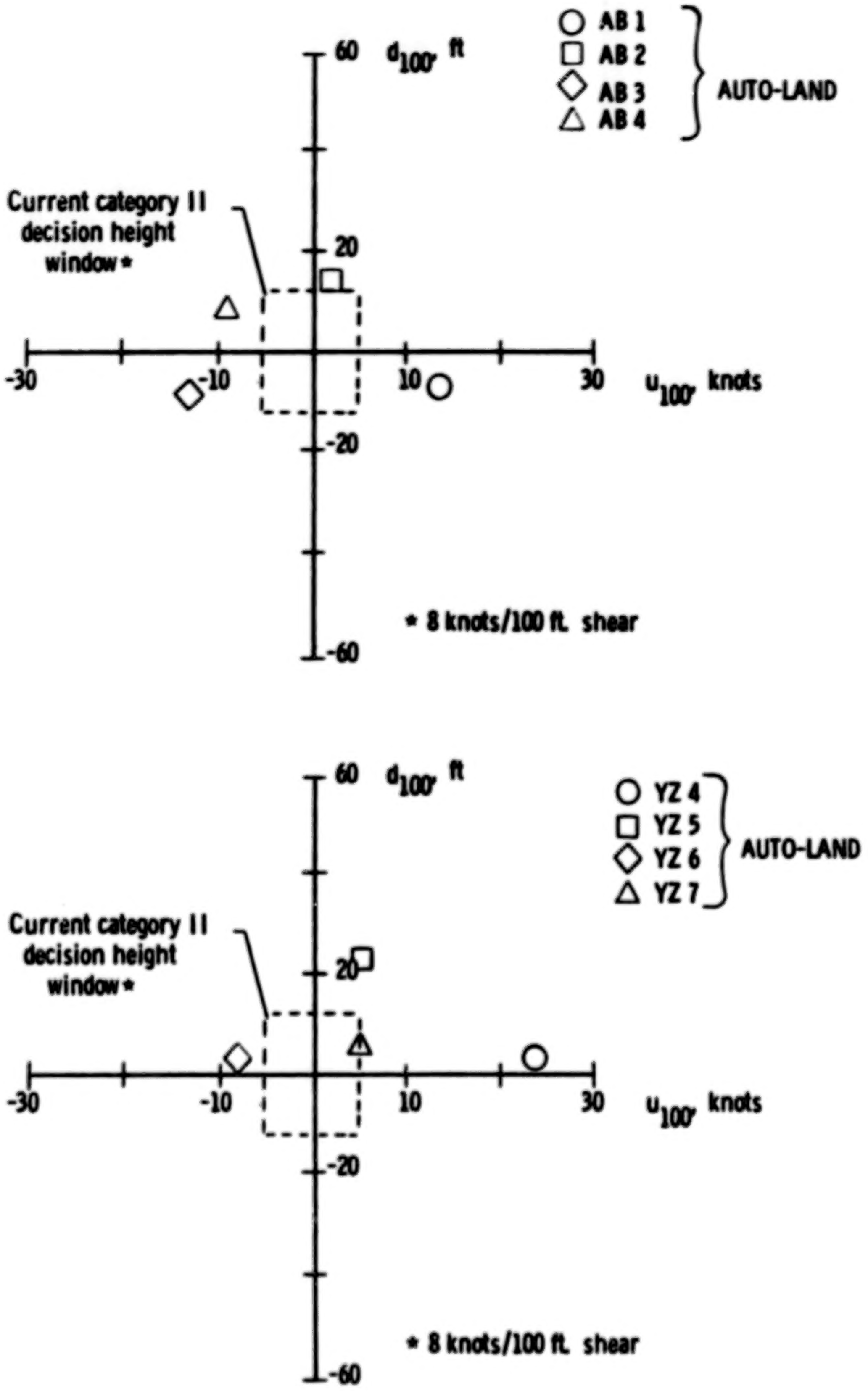


Figure 17.- Preliminary results for AB and YZ paths: Longitudinal decision height window-- Category II approach criteria.

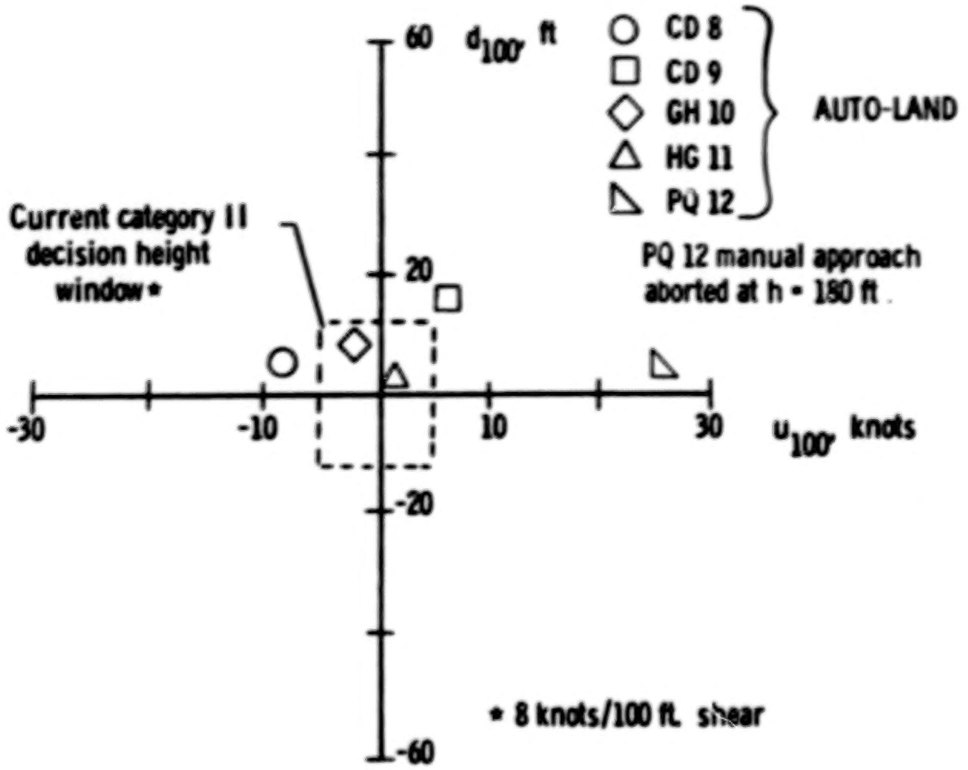


Figure 18.- Preliminary results for other selected paths: Longitudinal decision height window--Category II approach criteria.

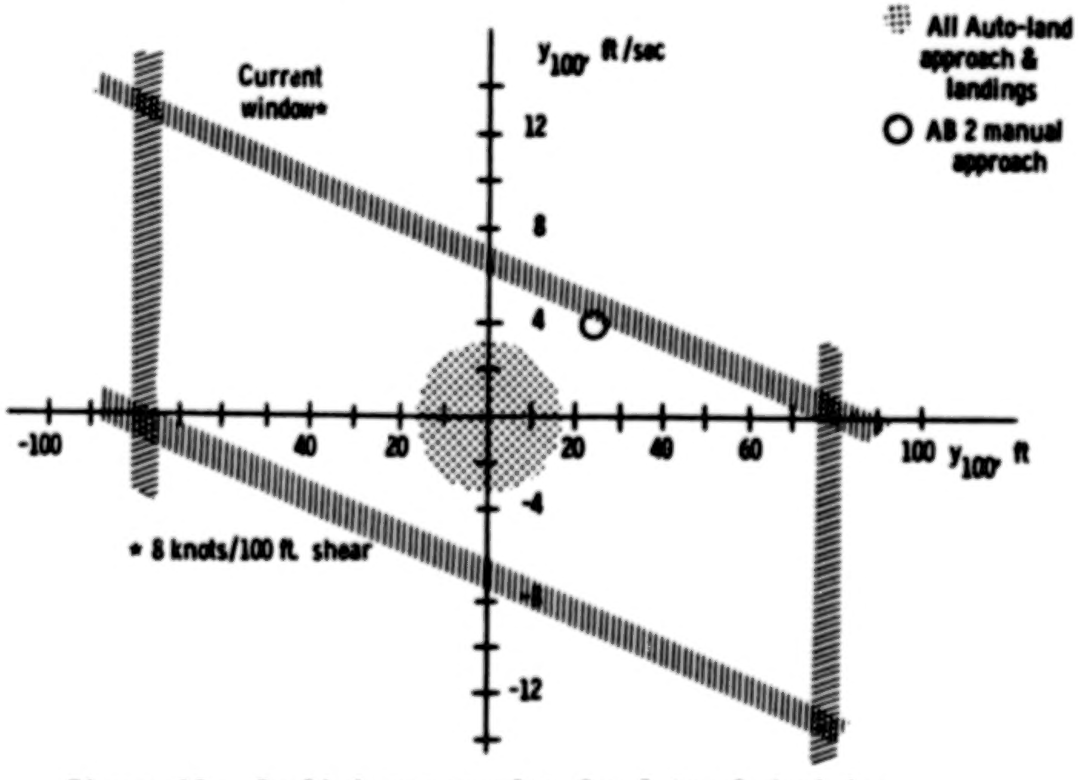


Figure 19.- Preliminary results for lateral decision height window--Category II approach criteria.

of the runway means that the combination of current lateral deviation and lateral deviation rate (cross track velocity) at the decision height results in a projected touchdown point that is still on the runway. As seen in Figure 19, all autoland approaches for the twelve selected approach paths fell within the lateral decision height window. The manually flown approach for path AB 2 produced a combination of lateral position offset and cross track velocity error very close to the stipulated decision height window.

Figure 20 illustrates the touchdown dispersion for the twelve autoland approaches as referenced to an acceptable landing region for a standard runway. The acceptable landing region is computed based on the two sigma criteria shown in Figures 15 and 16. Note that the manual approach for path AB 2 resulted in touchdown position which was slightly outside the acceptable landing region. A number of the selected paths resulted in automatic landings that were outside the acceptable landing region. These particular landings were generally longer and hotter due to the positioning of the microburst relative to runway threshold. For these cases, the airplane typically experienced a decreasing head wind shear or a head wind shearing to tail wind in such a way as to dramatically increase groundspeed prior to touchdown. Figure 21 shows a touchdown dispersion comparison between JAWS wind shear penetrations and the same simulator system flown against the 21 SRT wind shear profiles. No crashes occurred as a result of flying in the JAWS wind shear environment; however, the flight system was unable to negotiate three of the SRI profiles and crashed short of the runway. Figures 22 and 23 provide additional summary data collected during the JAWS wind shear simulation study, including touchdown criteria for state variables other than those mentioned previously, pilot comments, and wind shear severity ratings for the twelve selected paths.

The JAWS wind fields appear to be data rich and provides a multiplicity of wind shear profiles exhibiting subtle inflections and large dynamic range. Inherent properties of the wind fields provide abundant quantitative and qualitative wind shear clues including cross wind shear. Pilot perception of wind shear severity and attendant missed-approach decision depends strongly on shear phasing relative to runway and magnitudes of wind gradients encountered. A preliminary simulator experiment indicated performance violations, based on 100 ft. decision height criteria and acceptable touchdown dispersion for the candidate flight system studied.

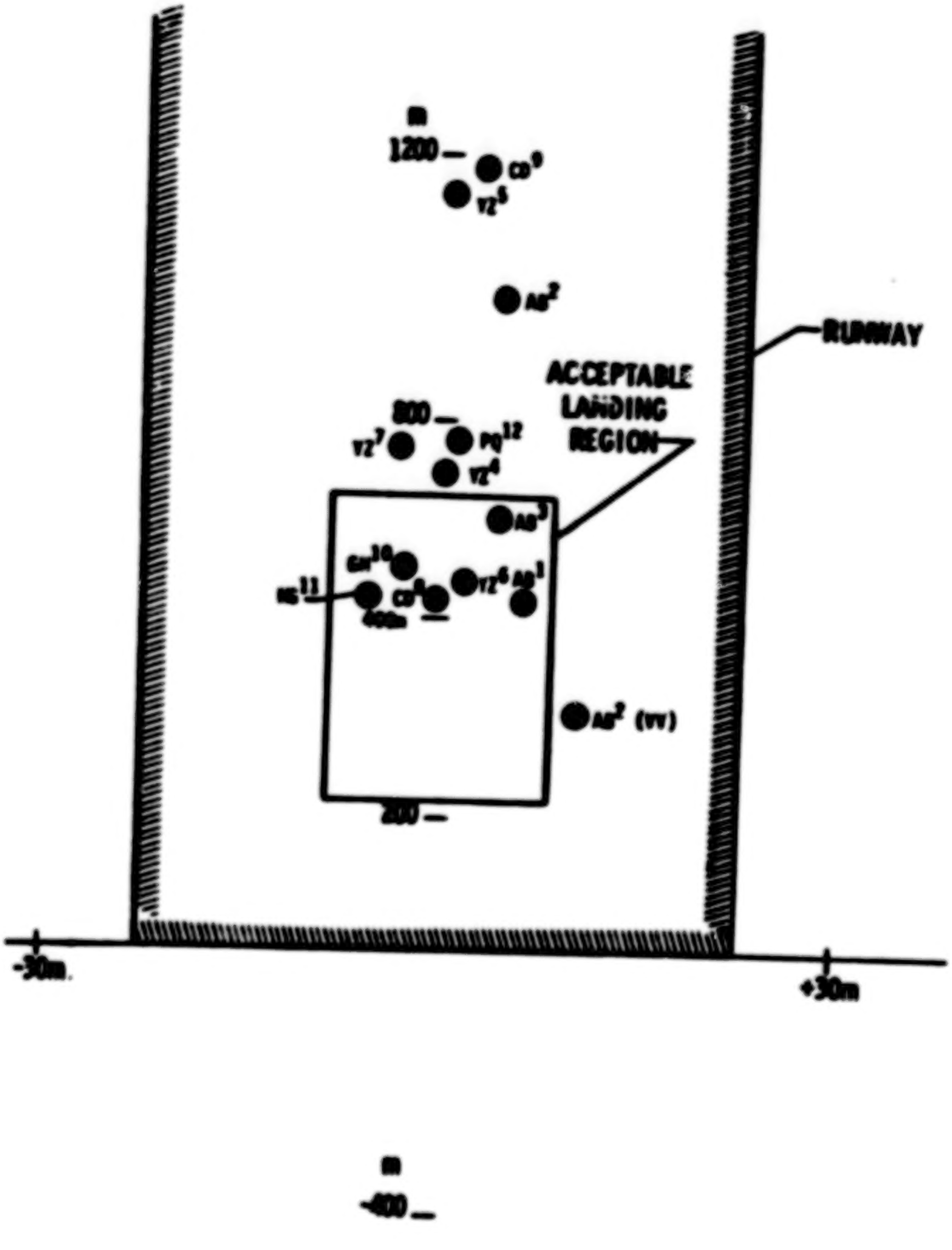

m
1200
CD^9
VZ^5
AG^2
RUNWAY
ACCEPTABLE LANDING REGION
800
VZ^7
PQ^{12}
VZ^4
AG^3
GH^{10}
VZ^6
AG^1
MG^{11}
CD^8
400m
AG^2 (VV)
200
-30m
+30m
m
-400

Figure 20.- Touchdown dispersion.

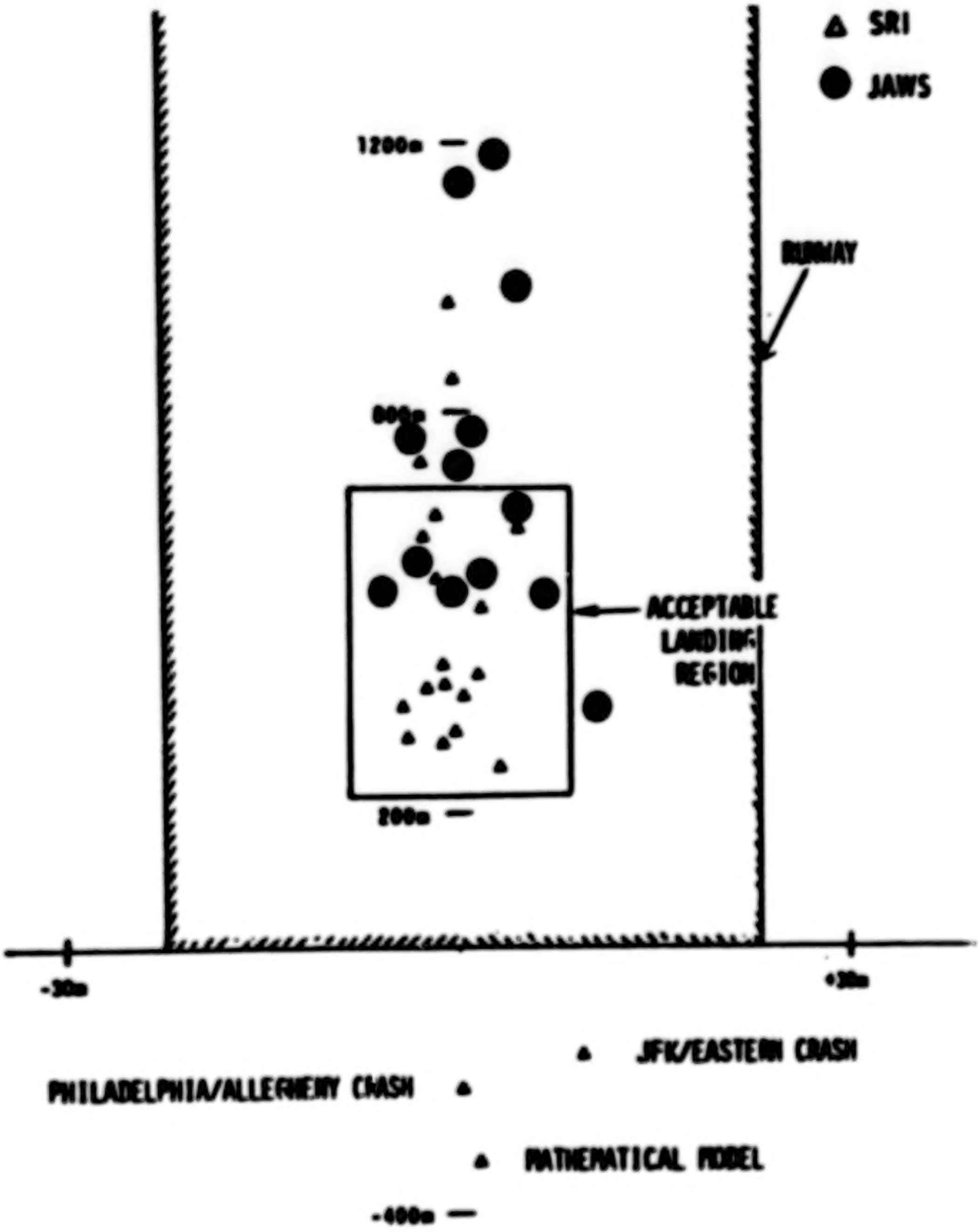


Figure 21.- Touchdown dispersion comparisons for SRI and selected JAWS wind shears.

FLIGHT PATH LABEL	TOUCHDOWN CRITERIA									COMMENTS
	X_{TD}	$\dot{h}_{TD}$	θ_{TD}	u_{TD}	C_L	Y_{TD}	$\dot{Y}_{TD}$	β_{TD}	ϕ_{TD}	
AB 1										All touchdown parameters in tolerance
AB 2	X		X	X						$U_{TD} > 1.3\ U_{stall}$, nosewheel landing, approach not stabilized
AB 3										All touchdown parameters in tolerance
AB 2 (manual)						X				CAS = 98 knots at h = 220 feet, stick shaker, AOA warning
YZ 4	X		X	X						$U_{TD} > 1.3\ U_{stall}$, nosewheel landing, approach not stabilized
YZ 5	X		X	X						$U_{TD} \gg 1.3\ U_{stall}$, nosewheel landing, autothrottle limit cycle
YZ 6										All touchdown parameters in tolerance
YZ 7	X		X	X						$U_{TD} > 1.3\ U_{stall}$, nosewheel landing, insidious flight path de-stabilization
CD 8										All touchdown parameters in tolerance
CD 9	X		X	X						$U_{TD} \gg 1.3\ U_{stall}$, nosewheel landing, approach not stabilized
GH 10										All touchdown parameters in tolerance
HG 11										All touchdown parameters in tolerance
PQ 12	X		X	X						$U_{TD} \gg 1.3\ U_{stall}$, nosewheel landing, autothrottle limit cycle
PQ 12 (manual)										Abort landing at h = 180 feet, executed go-around

X - Denotes unacceptable performance

Figure 22.- Touchdown criteria.

FLIGHT PATH LABEL	PILOT RATING			COMMENTS
	+ SEVERE -	+ MODERATE -	WEAK	
AB 1		← X		Engine spool down cause for concern, go around at 520 feet Based on airspeed change
AB 2		← X		Go around based on airspeed change, horizontal shear noted
AB 3		X		Pilot went head-up, co-pilot would go around nose down attitude unacceptable, pilot decision to proceed marginal
YZ 4		X		Go around at 400 feet, based on airspeed change
YZ 5		← X		Go around at 100 feet, based on glide-slope error
YZ 6			X	Pilots monitored wind changes well
YZ 7		X →		Go around, high and fast
CD 8			X	Pilot apprehensive engine spool down, noted slight airspeed loss
CD 9		X		Go around at 100 feet, high and fast
GH 10			X	Apprehensive about spool down, "see this everyday"
HG 11			X	Noted down draft at 750 feet
PQ 12		X		Go around at 440 feet, airspeed loss, high pitch attitude

Figure 23.- Pilot rating.

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3. Criteria for Operational Approval of Airborne Wind Shear Alerting and Flight Guidance Systems. Advisory Circular 120-41, Federal Aviation Administration, November 1983.

4. Frost, Walter; and Bowles, Roland L.: Wind Shear Terms in the Equations of Aircraft Motion. J. Aircraft, Vol. 21, No. 11, 1984, p. 866.

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APPLICATION OF DATA TO PILOTED SIMULATORS

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INTRODUCTION

In this paper, I will address the application of a further-developed analytical model and JAWS data to a piloted simulator. What I have to say comes from the viewpoint of a user of wind shear data. I became involved with wind shear models back in the late 1970's in the course of several accident investigation simulations, and in participation with the FAA wind shear programs at NASA Ames. Later, I used wind shear models in the course of evaluating cockpit displays. At one point, shortly before the JAWS Project, I was using a simple three-dimensional outflow model. I am sure there are others trying the same approach in piloted simulation.

Our objectives at Ames arose as a target of opportunity. We now have a new facility established by our Human Factors Group. It includes a new 727 simulator--Singer-Link advanced technology system--and is a duplicate of a recent acquisition by Delta Airlines, with Phase-2 specifications. It was an attractive opportunity to provide a facility for the development of piloting procedures, and for the selection of training scenarios, as well as for any objectives that might result from a workshop such as this. Currently the system is operational with the new shear models and comprehensive data output. It has been demonstrated to a group from United Airlines, many of whom are participating in this workshop; and in early May, it was reviewed by the Ad Hoc Committee. As we have not conducted any studies with the system to date, this is basically a progress report.

In this simulator, we have wind shear models from three sources. With the simulator, of course, came FAA wind shears. In our particular mechanization, we are using four of the six available. We have three JAWS corridor sets from the August 5 data, i.e., AB, IJ, and KL. We have five computed wind fields which are derivations of the simple outflow model that I was using in the R&D simulation. These various models are presented in the context of 34 test scenarios. We have both light- and heavy-weight takeoff and landing configurations which can be flown in a number of wind fields defined by the three types of models. Each of the wind fields within the scenario can be gained up or down in amplitude; i.e., all the wind variations are gained up or down simultaneously. A turbulence model is added, and its output can also be gained up or down. In the simulator, it is just a matter of calling up with the keyboard the desired scenario, adjusting the variables if we wish to change them from the nominal, and flying the takeoff and/or approach. The system will usually give us hard copy data within a short period of time.

This is a training simulator; we were dealing with facility and support personnel unaccustomed to the constant software changes seen in the R&D simulators, so we wanted to keep additions as simple as possible. That is why we used a two-plane corridor model from the JAWS August 5 data base. A turbulence model adds three components of turbulence. We are not equipped with the fourth component of turbulence which is often added into simulation, i.e., the spanwise gust variation which gives a discrete rolling input. Neither have we introduced gradients into the pitch and yaw rate damping terms, which are also usually in our research simulators. We use

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the basic Dryden turbulence model filters that accompany FAA wind shear models. Turbulence intensity and turbulence scale length are defined as functions of wind velocities and attitude similar to MIL SPEC 8785C (reference 1).

I am not concerned about the consequences of not adding the gradients to the system. This position is based on what we have seen in our research simulators as we operated with and without them. Yes, they do have a measurable effect; but in terms of the piloted simulation (the pilot's ability to deal with the shear and turbulence), I am not convinced that they are of major significance. We will be very interested in all the other experience that is assembled at this workshop on that matter. If and when we find that these gradients are essential to the objectives of our simulations, we will find some way of adding them.

The JAWS model has been described in some detail at this workshop. I will just reiterate that I used a two-plane model: 250 feet on either side of the nominal approach path is a defined plane, and we interpolate between them. As long as the pilot is not more than 250 feet on either side of the centerline, he is seeing as much as he would in the full data set.

Figure 1 describes the computed downburst model. We assume an axially symmetric downdraft column with a vertical velocity variation with respect to the axis that varies in the manner indicated in Figure 2. Below a defined height, vertical velocity varies with attitude as an exponential function, and the principle of continuity is used to define a horizontal dispersion of the flow. It's fairly simple; we define the radius, the altitude at which the dispersion starts, and the vertical velocity above that altitude. These values define the individual downburst field. I want to say that this model has no connection with the real world, except that it follows the laws of continuity. It is strictly a mechanism with which to create a wind profile in simulation of observed phenomena, i.e., a particular piece of JAWS data, or a particular profile recorded in an accident. It is not atmospheric science.

In Figure 3, the outflow starts at 1,600 feet; above that altitude, the downdraft is 20 kts. The radius of 2,000 feet defines the extent of the shear. The wind velocity profile near the ground is shown with respect to the axis at 6,000 feet. A total shear of 46 kts is shown. If I want to model something more elaborate I can, in our particular simulation, model up to five of these downbursts and add their effects to produce a particular sequence of along-path winds. Figure 4 is an attempt to simulate the August 5 AB corridor. We can come fairly close, but we get some downdrafts that are somewhat stronger than were shown in the August 5 data.

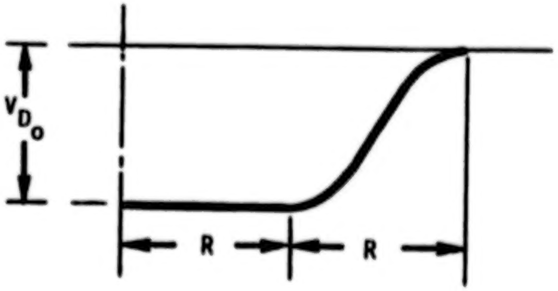
In Figure 5, the circles represent the four downbursts constituting the computed version of the JAWS shear. This construction is done empirically until the gradient being sought is achieved. The flow model on the right is actually an updraft, a change of sign on the vertical wind to produce a flow convergence.

Our model shown in Figures 6 and 7 attempts to match data on the New York/Kennedy shear recorded prior to the accident of 1975. In this case, the downdraft actually appeared before the shear and was fairly abrupt. The computed values shown don't include turbulence. The flight-recorded data did not refer to the accident airplane; it was from data gathered by an L-1011 a few minutes before the accident.

- Distance from downburst center, $r = (X^2 + Y^2)^{1/2}$
- Downdraft velocity:

  If $R < r < 2R$:

  $$V_{D_r} = V_{D_o} (1 - \cos \frac{r}{R} \pi)/2$$



- Variation with altitude, H, below H_T:

  $$V_D = V_{D_r} \left(1 - \left(\frac{H_T - H}{H_T}\right)^2\right)$$

- Reference radial velocity at $r = R$: $V_{R_o} = \frac{R \times V_{D_o}}{H_T} \left(\frac{H_T - H}{H_T}\right)$
- Local radial velocity: If $r < R$: $V_R = \frac{r}{R} \cdot V_{R_o}$

  If $R < r < 2R$: $V_R = V_{R_o} \left(\frac{r}{R} - 1.3 \left(\frac{r}{R} - 1\right)^3 + .45 \left(\frac{r}{R} - 1\right)^6\right)$

  If $r > 2R$: $V_R = 2.3 \frac{R}{r} \cdot V_{R_o}$
- $V_x = \frac{x}{r} \cdot V_R$, $V_y = \frac{y}{r} \cdot V_R$

Figure 1. A simple downburst model.

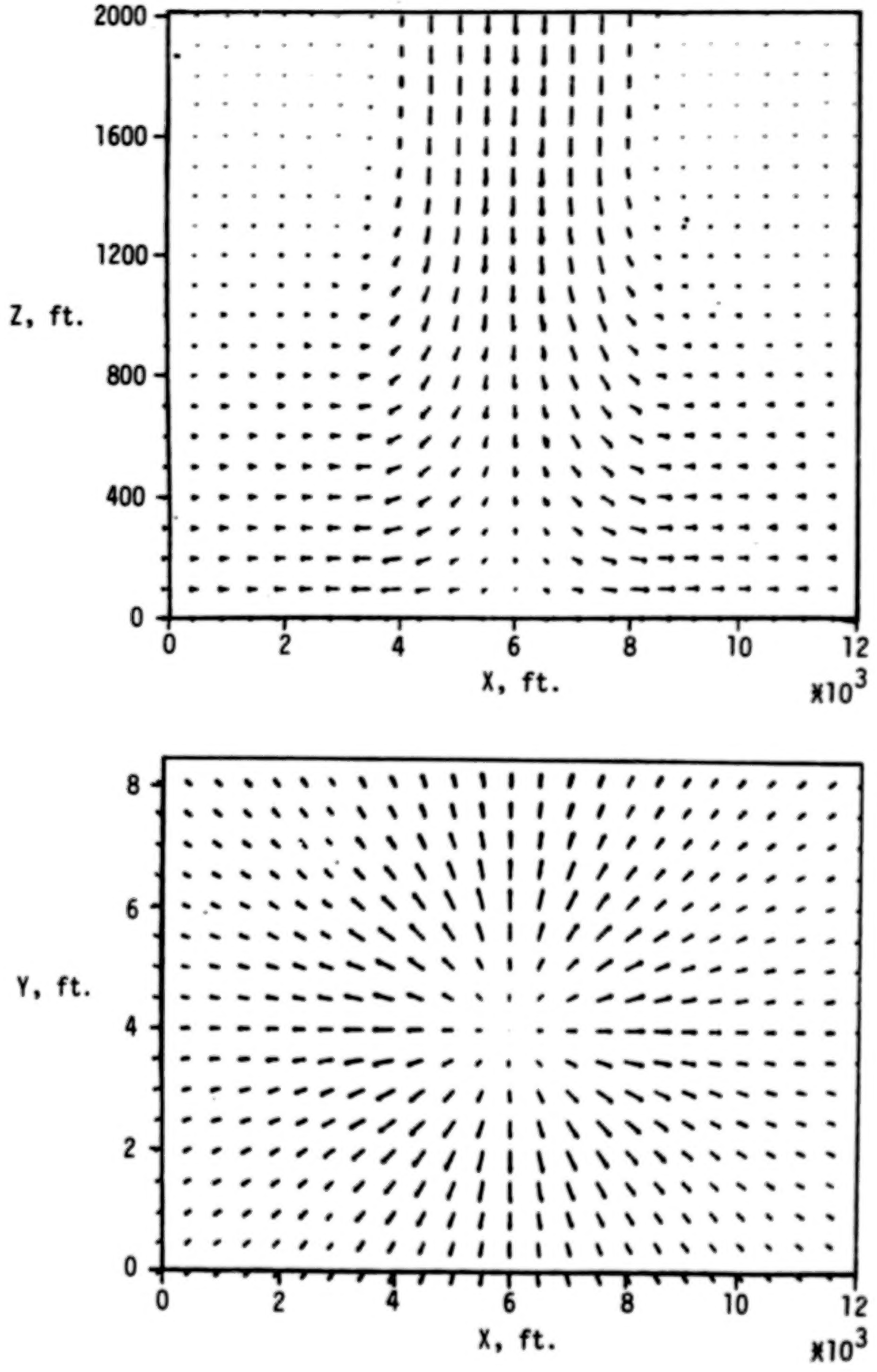


Figure 2. Elements of a Downburst.

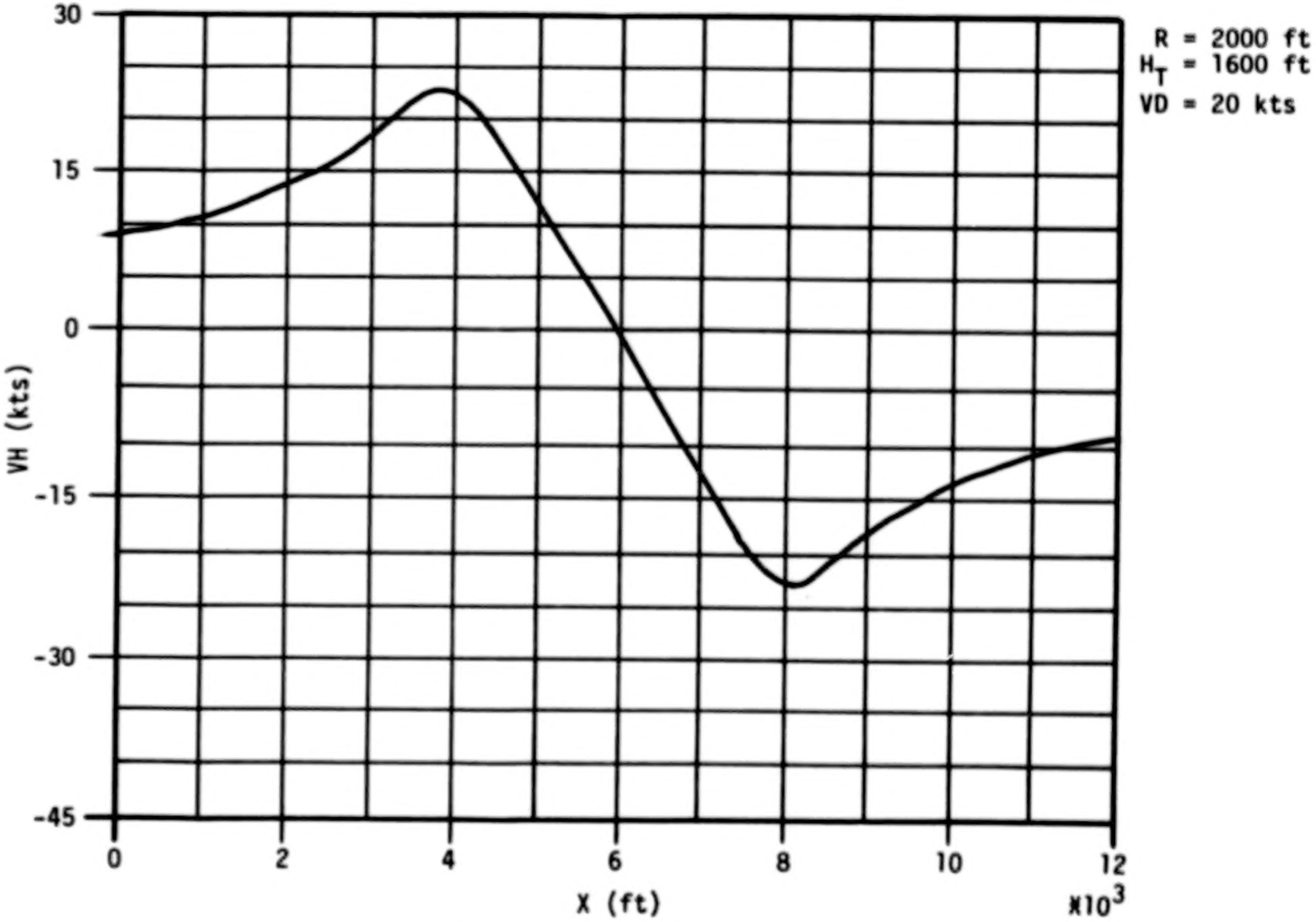


Figure 3. Wind Velocity.

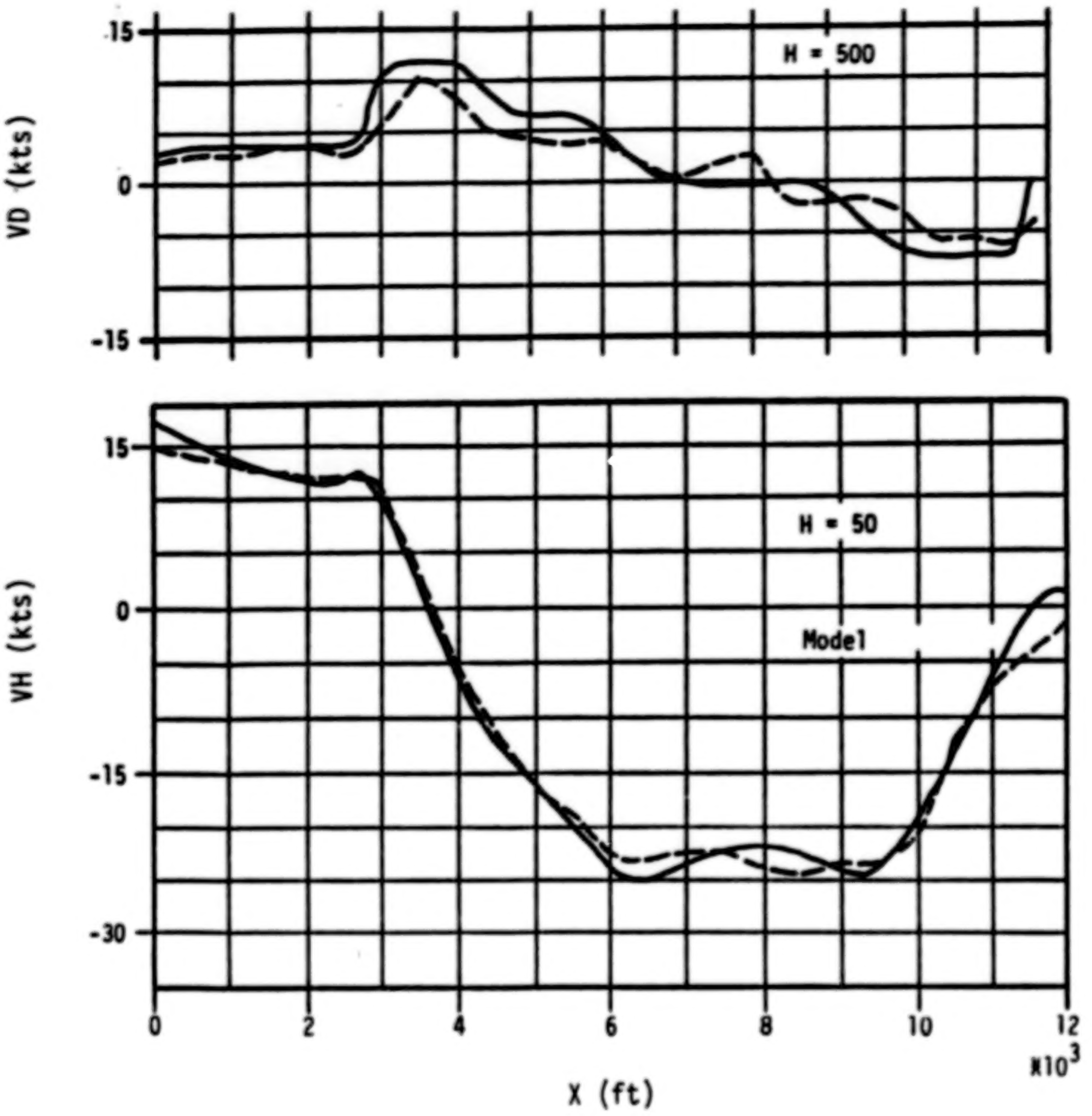


Figure 4. JAWS August 5 AB Modeled.

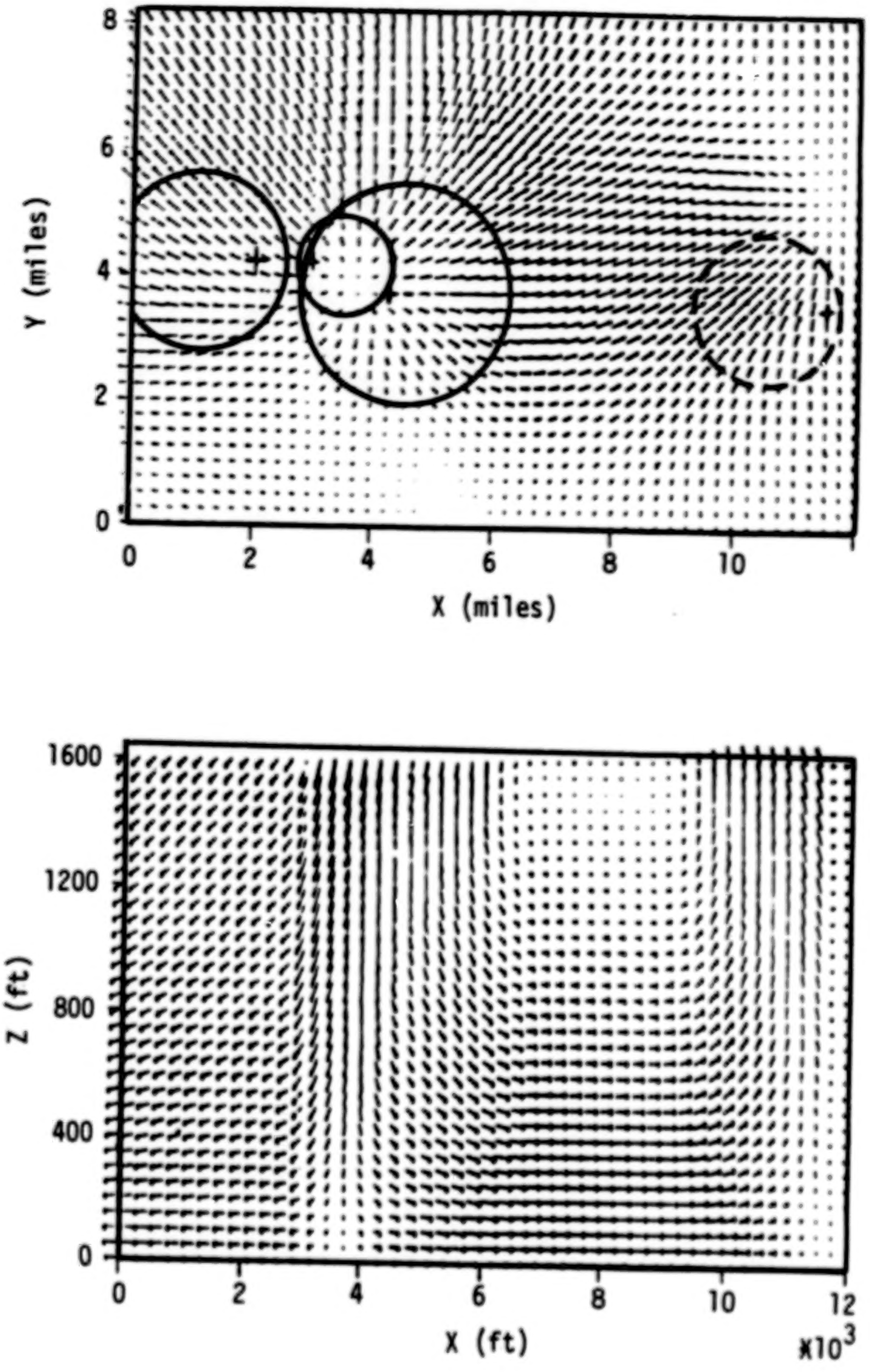


Figure 5. Modeling JAWS August 5 AB.

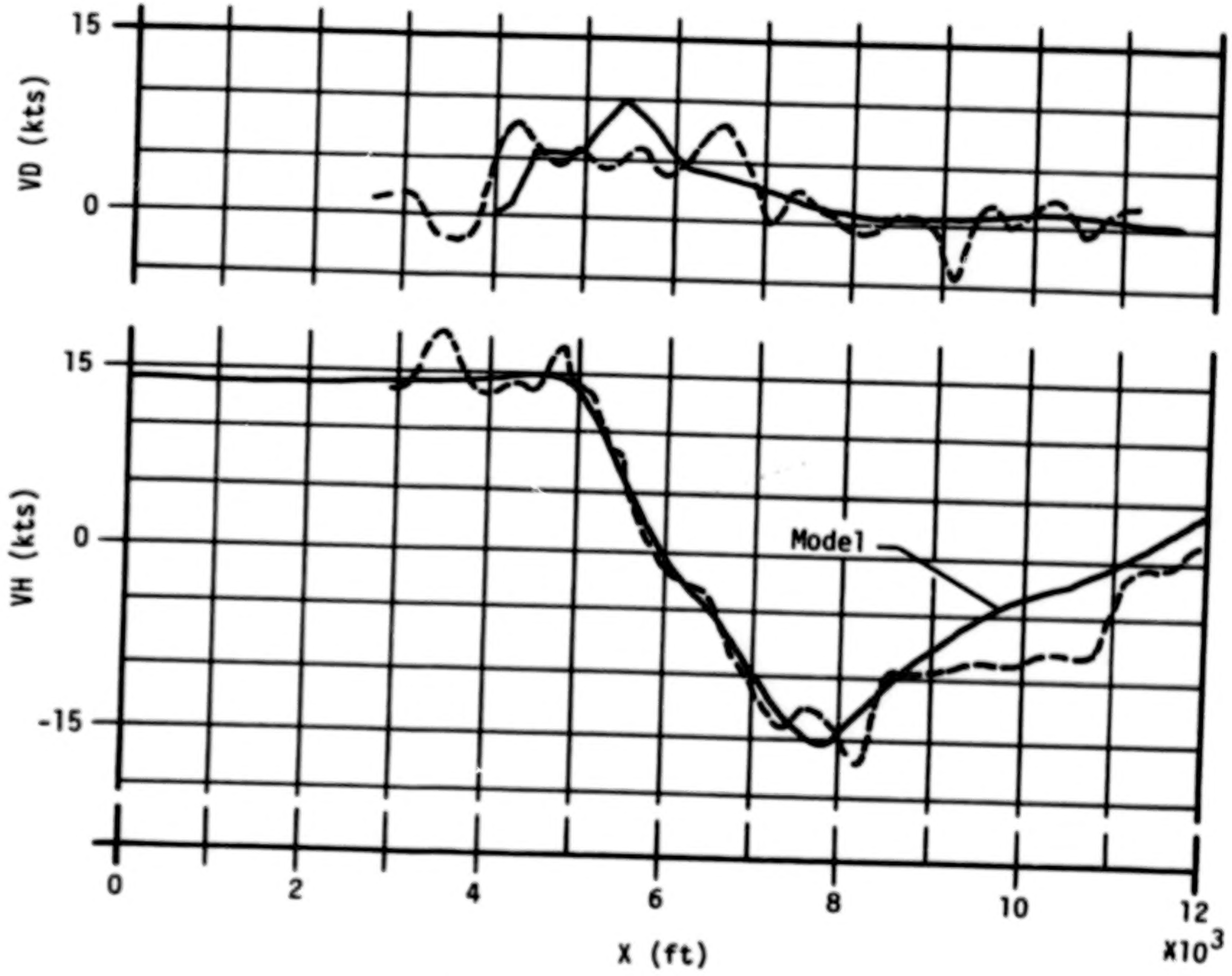


Figure 6. New York Shear Modeled.

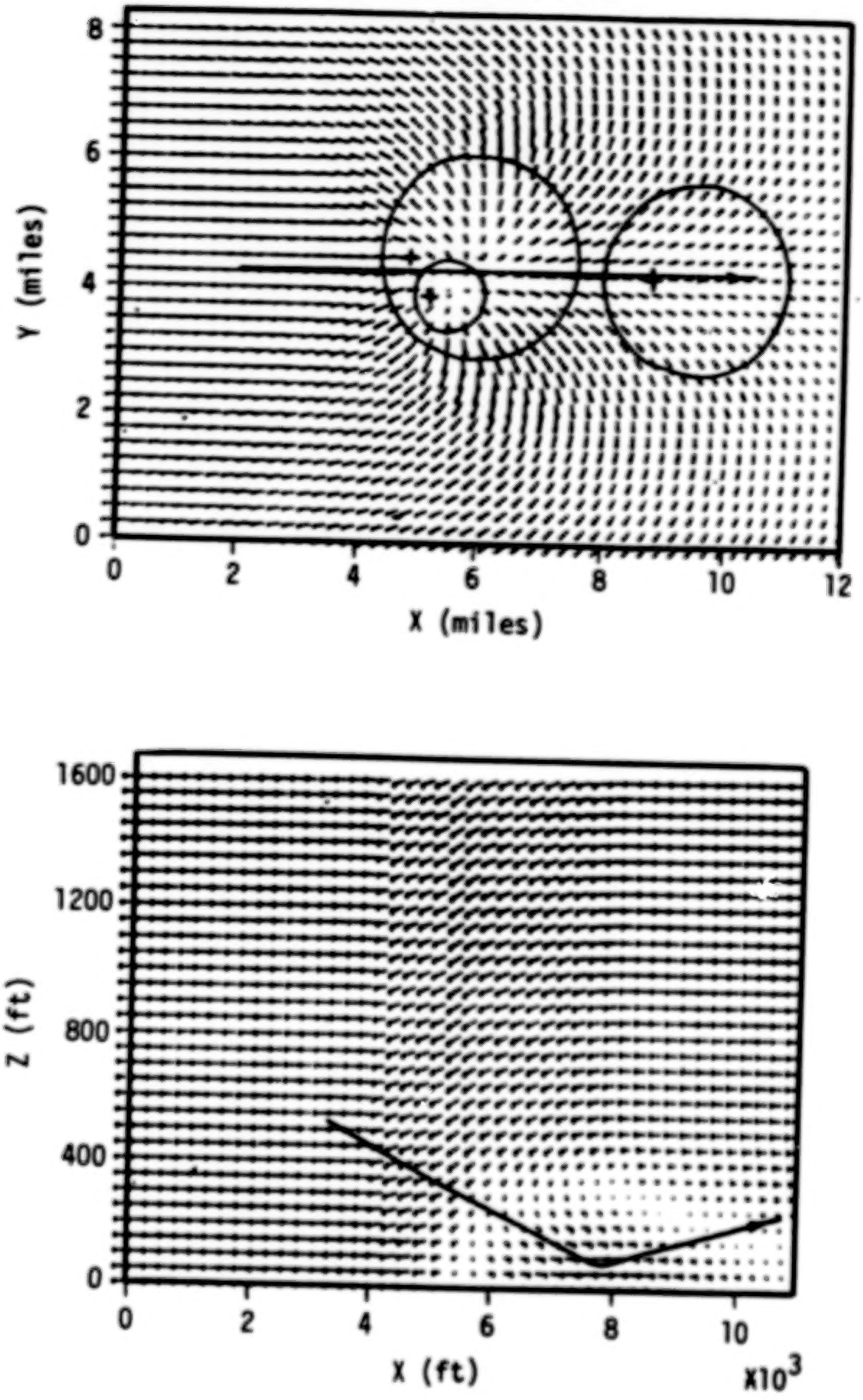


Figure 7. New York Shear Model.

An incident occurred in Tucson in 1977 where the pilot encountered a shear before he could achieve rotation speed, which was about 128 kts. The recorder data indicated he ran down the runway for a good 10 seconds with no increase in speed. He finally got an increase in speed, rotated, lifted off, then proceeded to lose speed with no climb, and flew through high-tension wires. He should not have survived, but he did. This is just an example of the variety which is out there. From that event, a wind model or profile can be deduced showing an interruption in the shear gradient, as represented by the dashed line in Figures 8 and 9. We model this particular profile with one large outflow model and a small upflow model in the middle of it to cancel the gradient.

We have not done a lot of systematic work with these models in the 727 simulator, but Figures 10 through 15 depict data from some approaches and takeoffs, with time in seconds shown along the bottom. The lowest of the plots shows the three components of wind. We have described the first case, Figure 10, as scenario 14. It is a heavy takeoff--a 727 at 175,000 lbs--flying through JAWS I (which is AB in this case) and moving 5,000 feet down past the glidepath intercept point on the runway, or actually 6,000 feet from threshold. In this case, we have applied a gain factor of 1.3 to the winds. The winds shown come out of the JAWS data with the addition of some turbulence. We have a head wind of about 30 fps reducing to 25 fps; then there is a very rapid shear to a 50 fps tail wind. In this case, we are getting a total of about 52 or 53 kts of shear, and there is, of course, some vertical and lateral wind. The airplane was accelerated to 139 kts rotation speed, smoothly rotated to about 14°, then encountered the shear. We see about 30 lbs of stick force during that rotation, with the release of stick force as the takeoff attitude is attained. The speed attained is V-2 plus 10. The airplane is climbing nicely; but then off comes the airspeed as the shear is encountered, the nose drops from about 13° to about 7° attitude. The pilot is starting to sense that the aircraft is dropping and is adding back pressure; but the nose drops and the descent rate continues. The shear ends, speed increases, and flight path is recovered but not before the aircraft is back down to 50 feet. This is reasonable reproduction of what happened in New Orleans. Figure 11 is a repeat; the same profile. You will notice a few detail differences because the turbulence is going to make small high-frequency differences in the model. There isn't the release in the stick force, and, in fact, the nose isn't allowed to drop below about 11°. We see loss of airspeed by a few more knots which is not a great deal. In this case, emergency thrust was added at minimum airspeed, and there is a flyaway with essentially no altitude loss. These data comprise a demonstration of optimum versus non-optimum performance in the particular circumstance.

Figure 12 involves the same JAWS profile moved into a landing situation. In this case, it is not gained up, and there is no turbulence. The wind has very little high-frequency component. It was successfully flown through, but with the use of full takeoff thrust. It certainly would have been appropriate to go-around; the whole path was disturbed. In fact, I am not sure that a go-around didn't result from this; but, at least, the touchdown area of the runway was reached. In this case, without the amplification of the JAWS data, we are getting about 40-42 kts total shear. In Figure 13, we used the analytical model to produce a similar profile. Again, no turbulence was used. The shear is flown through with similar results. This airplane is running into the shear at about 250 feet altitude.

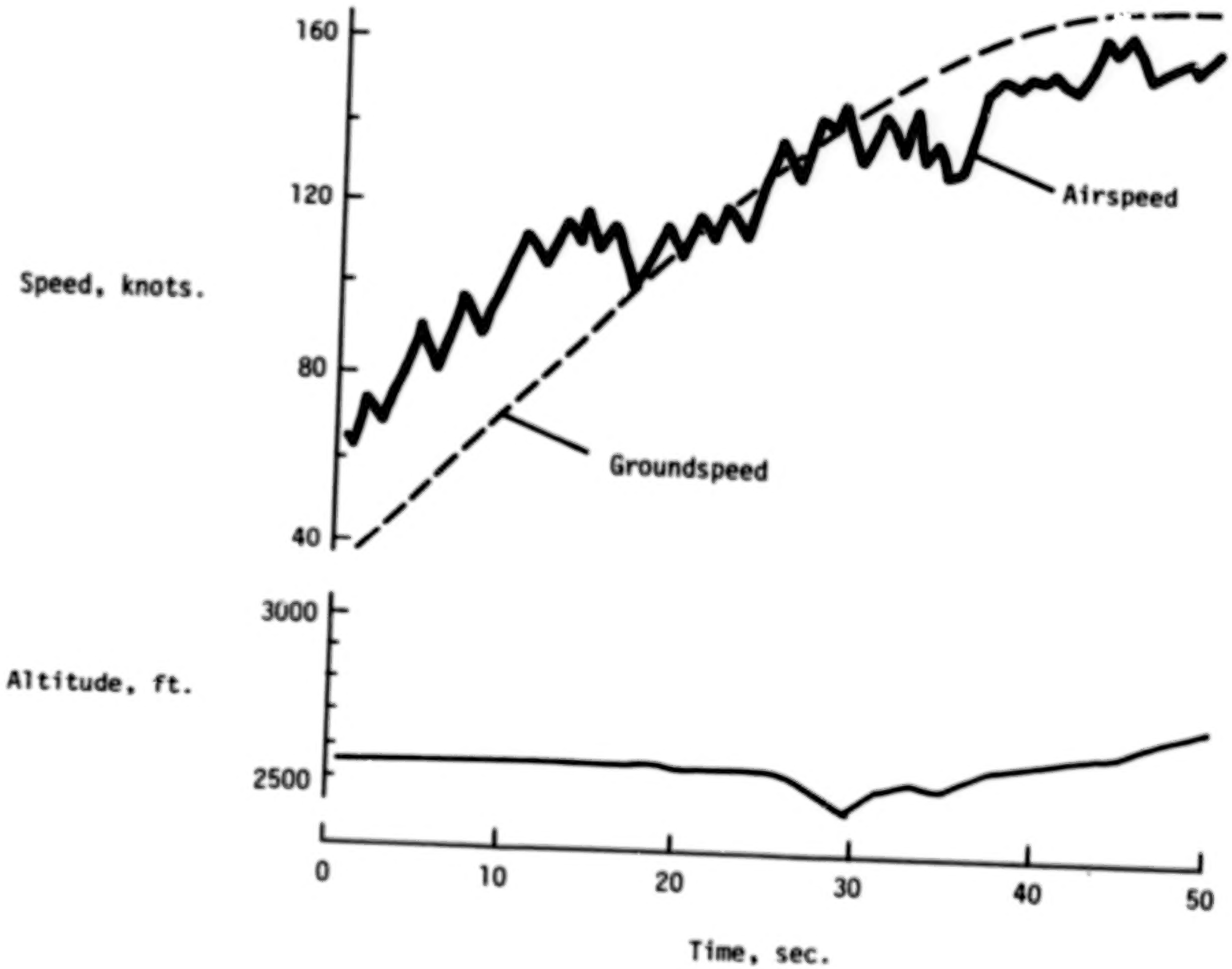


Figure 8. Takeoff Encounter, Tucson, 1977.

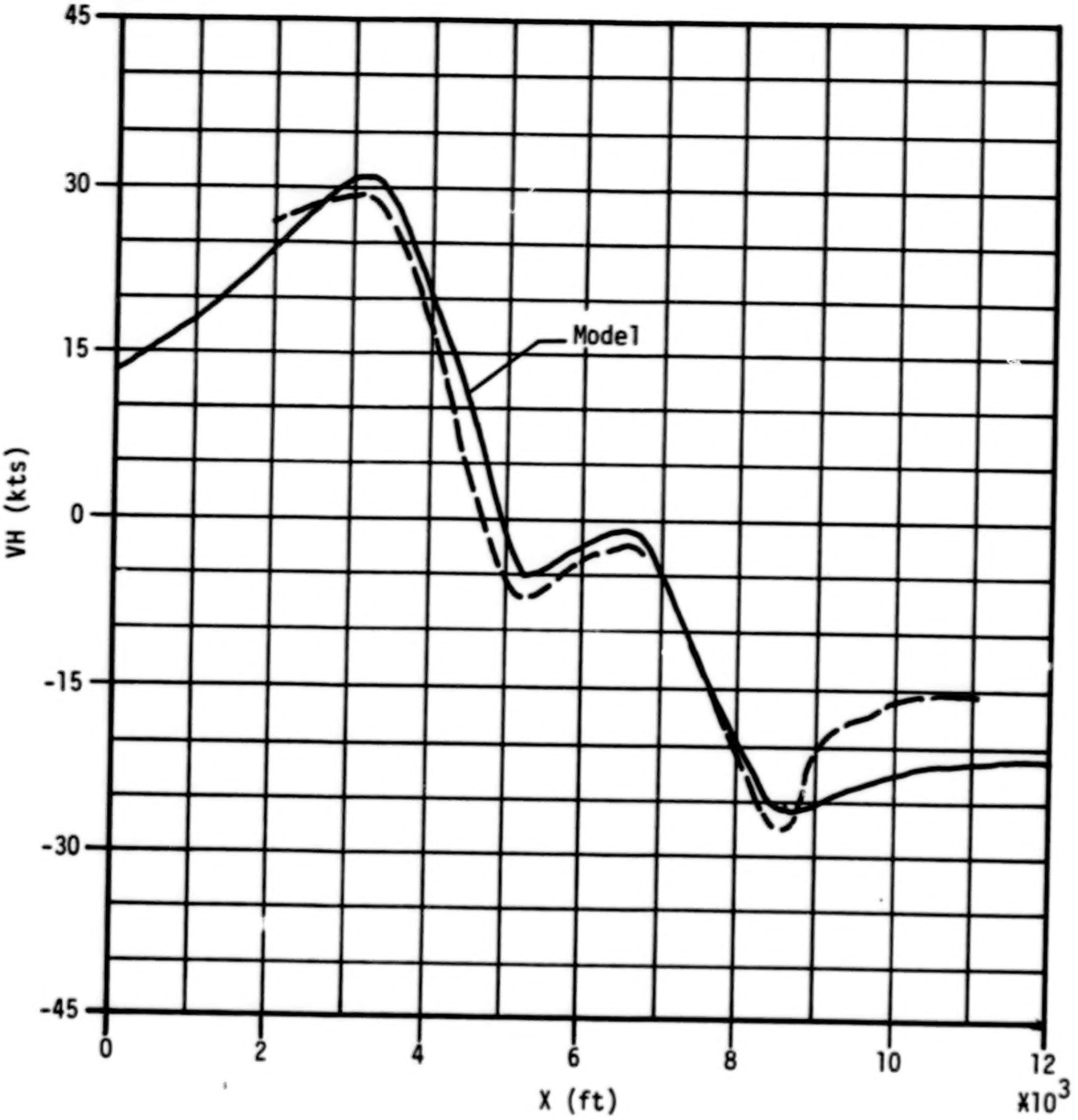


Figure 9. Tucson Shear Model.

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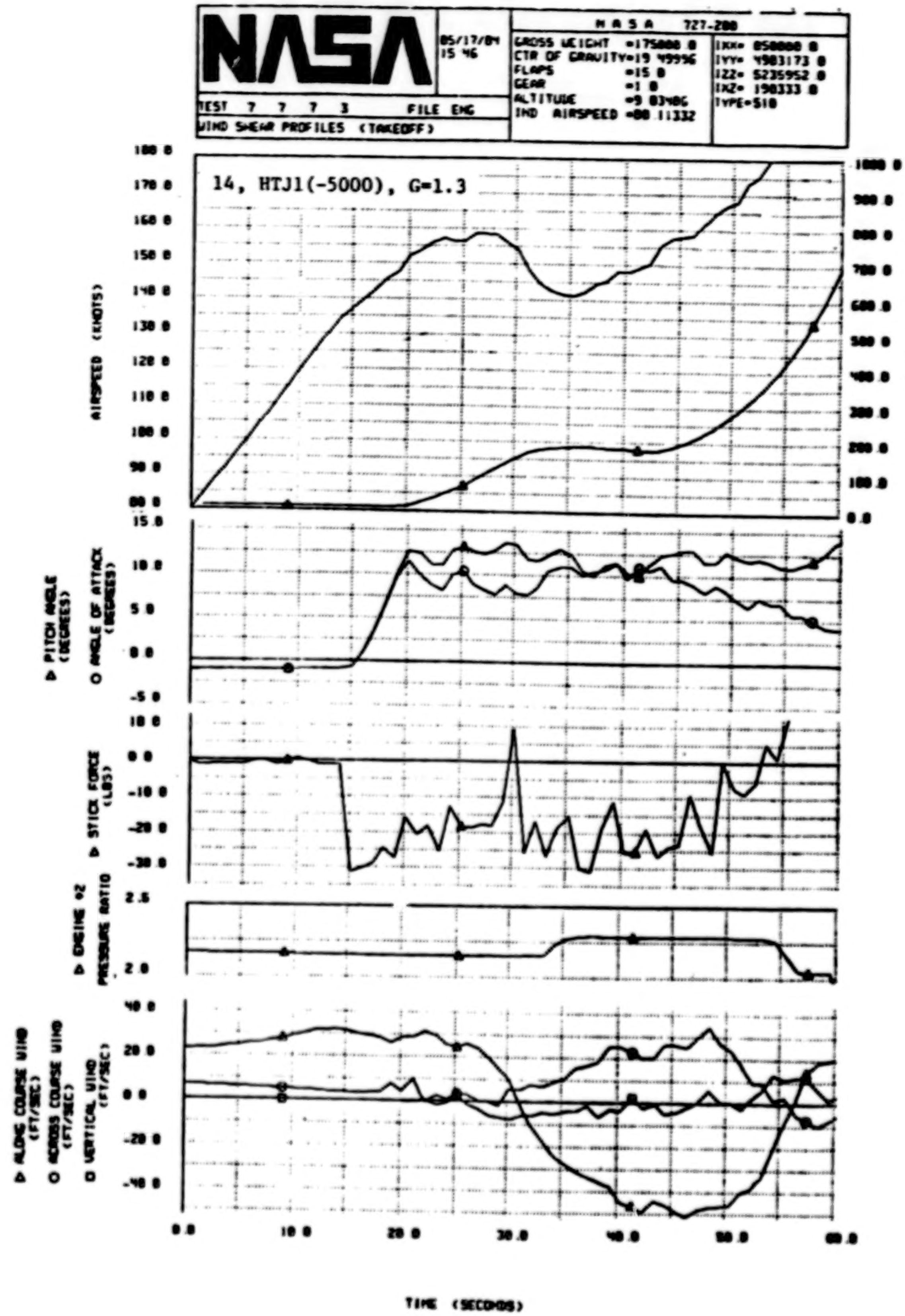

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15 46

TEST 7 7 7 3 FILE ENG

WIND SHEAR PROFILES (TAKEOFF)

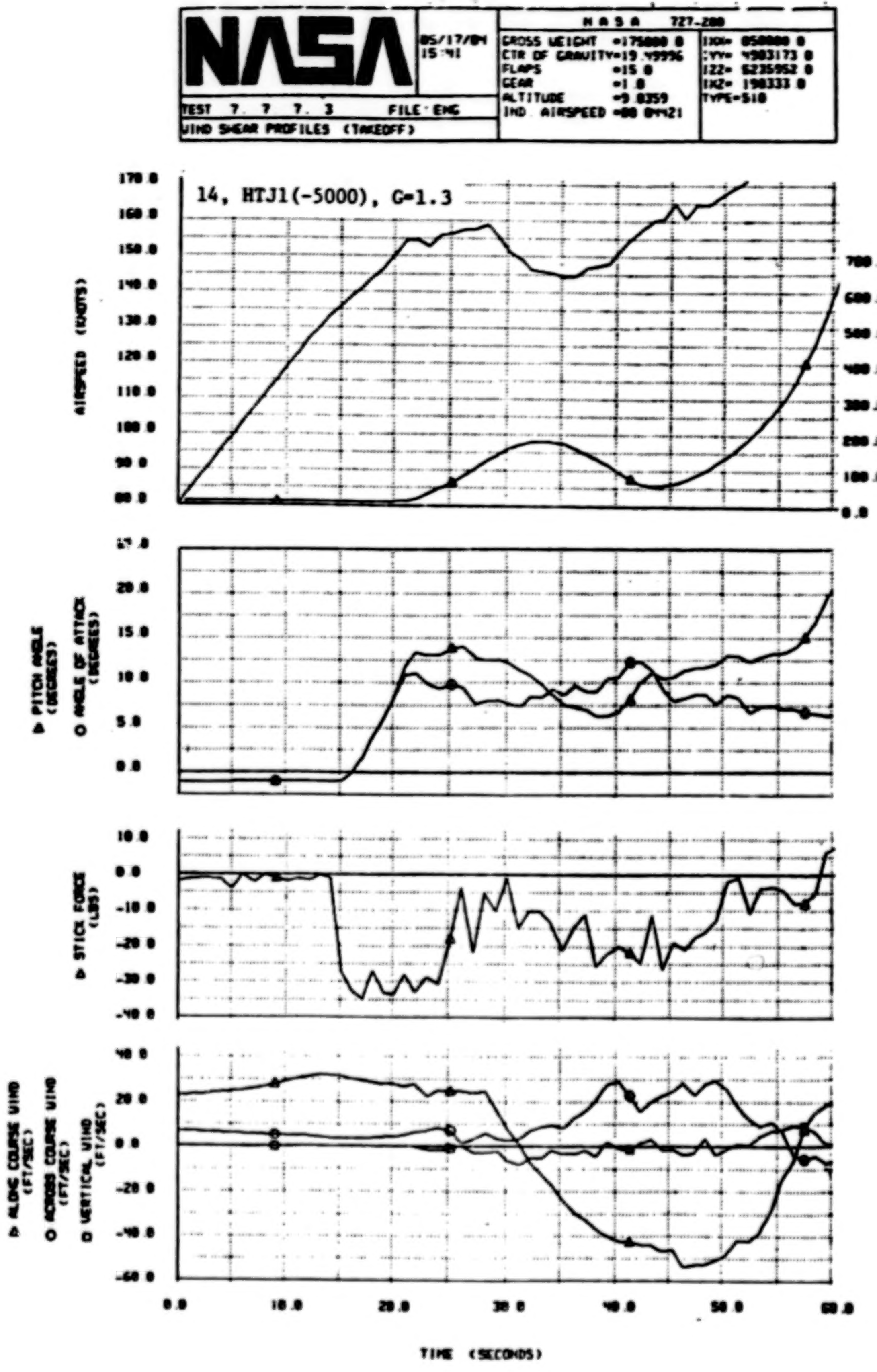
N A S A 727-200

GROSS WEIGHT =175000.0
CTR OF GRAVITY=19.49996
FLAPS =15.0
GEAR =1.0
ALTITUDE =9.03486
IND AIRSPEED =80.11332

IXX= 850000.0
IYY= 4983173.0
IZZ= 5235952.0
IXZ= 190333.0
TYPE=S10

14, HTJ1(-5000), G=1.3

Figure 10. Simulated Takeoff in Wind Shear--5/17/84, 15:46.



NASA 727-200

05/17/84 15:41

TEST 7. 7 7. 3 FILE ENG

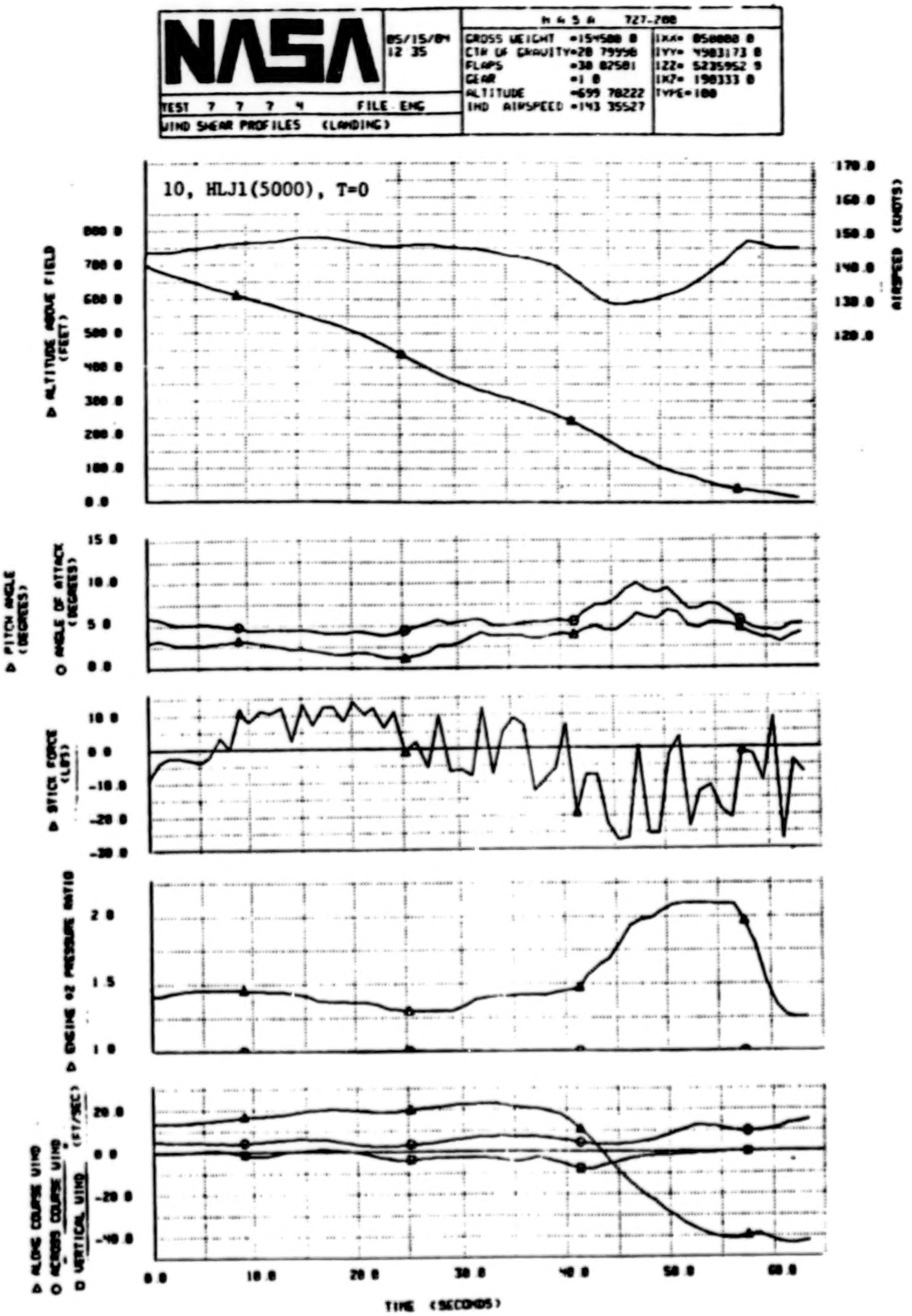
WIND SHEAR PROFILES (TAKEOFF)

GROSS WEIGHT =175000 0
CTR OF GRAVITY=19.49996
FLAPS =15 0
GEAR =1 0
ALTITUDE =9 0359
IND AIRSPEED =80 04421

IXX= 050000 0
IYY= 4903173 0
IZZ= 5235952 0
IXZ= 190333 0
TYPE=510

14, HTJ1(-5000), G=1.3

Figure 11. Simulated Takeoff in Wind Shear--5/17/84, 15:41.



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12 35

TEST 7 7 7 4 FILE ENG
WIND SHEAR PROFILES (LANDING)

N A S A 727-200

GROSS WEIGHT =154500 0
CTR OF GRAVITY=28 79996
FLAPS =30 02501
GEAR =1 0
ALTITUDE =699 70222
IND AIRSPEED =143 35527

IXX= 050000 0
IYY= 4903173 0
IZZ= 5235952 9
IXZ= 190333 0
TYPE=100

Figure 12. Simulated Landing in Wind Shear--5/15/84, 12:35.

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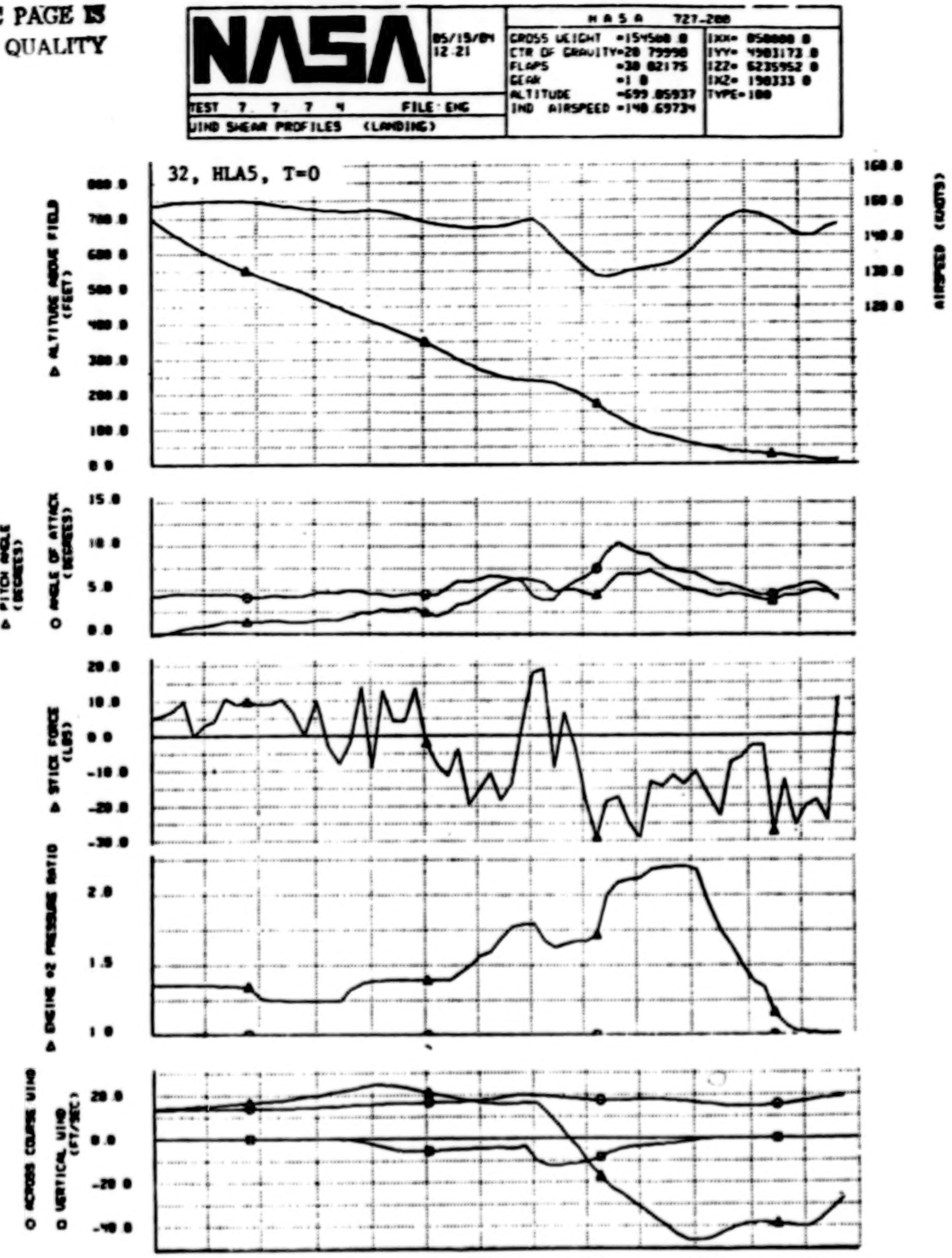

Figure 13. Simulated Landing in Wind Shear--5/15/84, 12:21.

Figure 14 shows the simplest possible model; a single downburst model with a distortion factor which makes the outflow move in one direction more than the other. We see a small increase in head wind, the gradient down to the peak tail wind component, and then the build-up on the other side. With the downdraft that goes along with the shear, we see the same piloting problems experienced in the previous takeoffs conducted with more complex models.

Figure 15 involves a Tucson-type of model where the airspeed has built up then has stopped increasing prior to rotation speed. The shear ends briefly, and the aircraft accelerates to rotation speed; the pilot rotates, encounters the other part of the shear, can't climb, and sits there flying just off the ground as the end of the runway approaches.

That is where we are right now. We are awaiting the results of this conference to tell us the best direction in which to go relative to the use of this particular capability. This is not the facility in which to conduct detailed research on the second-order effects of gradients. Training simulators do not have the desired software and data acquisition flexibility; but it does seem an obvious place to develop training scenarios and piloting techniques. We hope to find some good work for it.

QUESTION:

To what extent can your model be shifted with respect to the runway?

RESPONSE:

Just along the path. It can be shifted longitudinally along the approach or takeoff path.

REFERENCE

1. Military Specification--Flying Qualities of Piloted Airplanes. MIL-F-8785C, November 5, 1980.

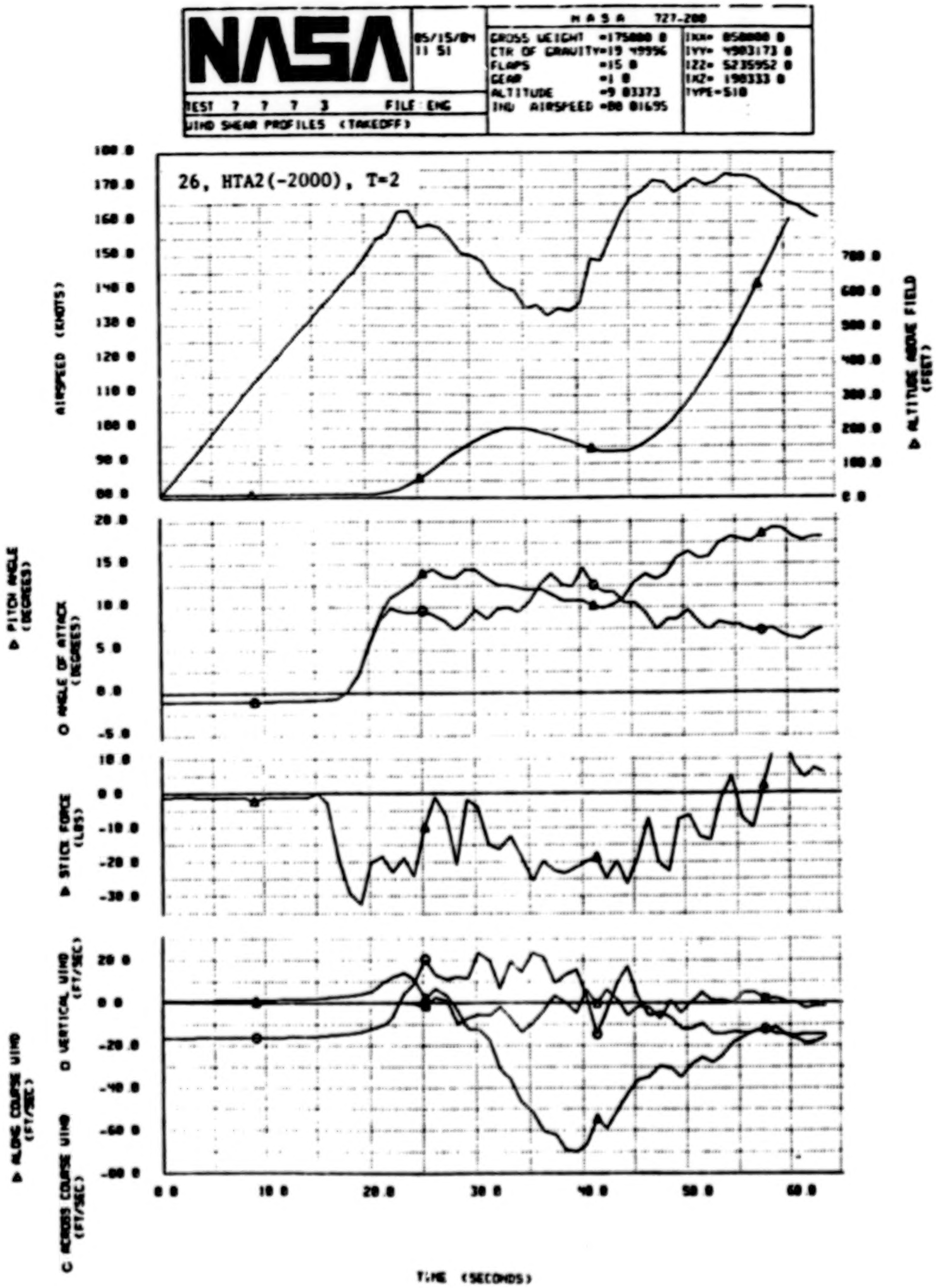

Figure 14. Simulated Takeoff in Wind Shear--5/15/84, 11:51.

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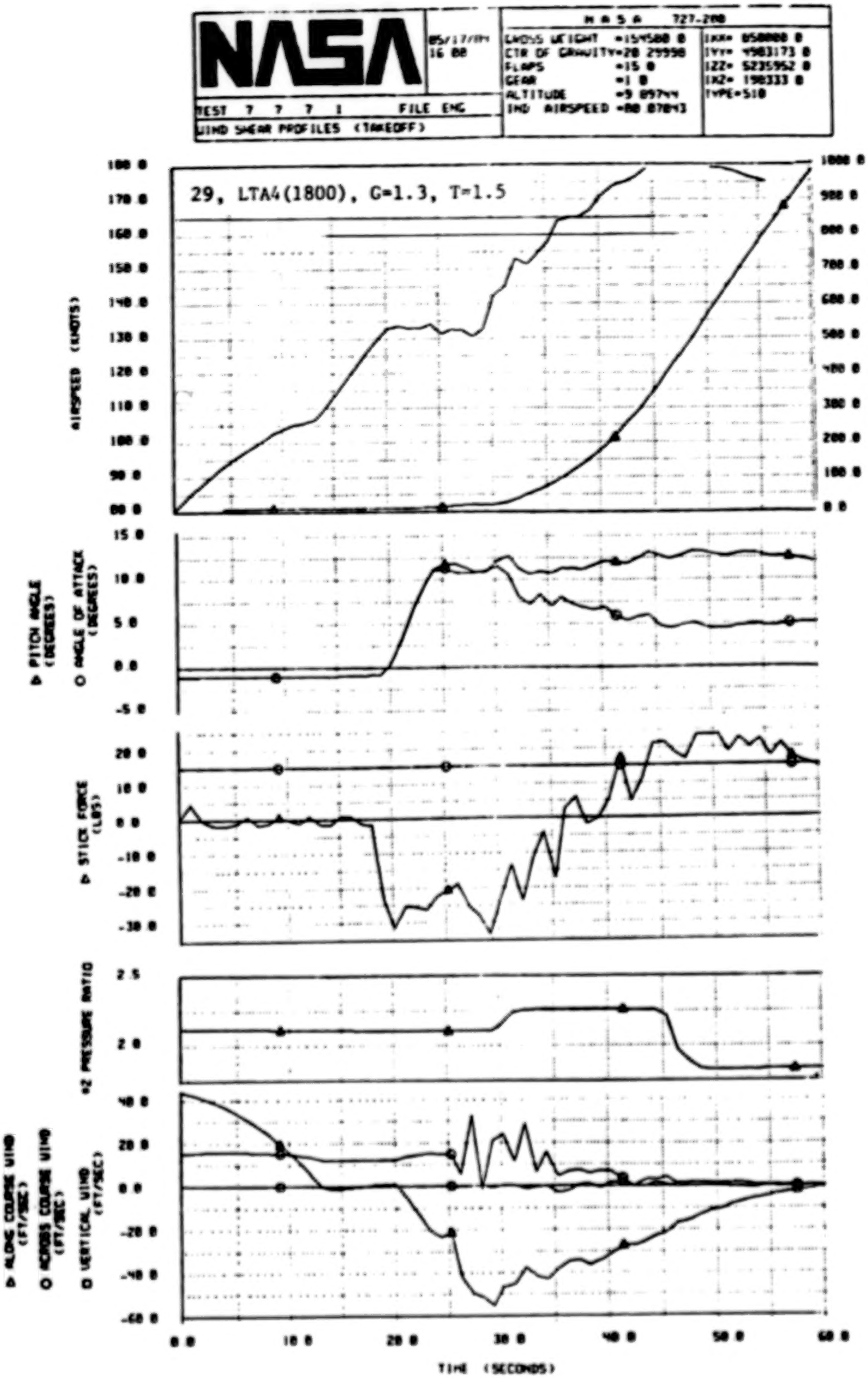

Figure 15. Simulated Takeoff in Wind Shear--5/17/84, 16:00.

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B-57B GUST GRADIENT PROGRAM

Dennis W. Camp
Program Manager
NASA Marshall Space Flight Center

INTRODUCTION

The NASA B-57B Gust Gradient Program (GGP), is a NASA multi-center program involving Ames Research Center and its Dryden Flight Research Facility; Langley Research Center; and Marshall Space Flight Center. The program objectives, along with photographs of the aircraft and other information on the effort, are given in Figure 1. As indicated in the figure, the primary objective of the program is to get wind gust data which can be used in new design criteria for aeronautical systems. The GGP data could also be used to provide turbulence information for use in simulation programs.

The need for new design criteria is readily seen if one considers this wind gust assumption; namely, that the wind varies only in the longitudinal direction (Figure 2). However, the left side of the figure illustrates the wind variation in a more realistic manner; that is, that the wind varies in the lateral, longitudinal and the vertical directions, as well as in time.

Indicated in Table I is the quantity of GGP data that has been collected to date, suggestions relative to enhancing and augmenting the facility, and tentative plans for additional data collection. Table II shows the distribution of the data with regard to location, degree of turbulence, and whether in rain or not. This information was ascertained from the flight engineer's notes for each of the flight tests. Of the data listed in Table I, only a small amount has been analyzed. The data analyzed so far consist of three sets of data from the flight tests in conjunction with JAWS, and two sets from the flight tests at NASA Marshall Space Flight Center (NASA/MSFC). None of the other data have been reviewed at this time. However, it is planned that all of the data will be analyzed in detail in the near future.

The data chosen for analysis, JAWS and NASA/MSFC, were selected for specific reasons. Namely, the JAWS cases were chosen because of the desire to investigate low-level turbulence (below 1,500 feet) associated with wind shear. Thus, the three JAWS data sets selected had severe turbulence, and also encompassed takeoff, level flight, and approach data. An example of this data is given in Figure 3. In this figure, U is longitudinal, V is lateral, and W is the vertical component of the wind as measured at the nose boom of the B-57B. The bottom three plots are the wind speed differences between the wing tip booms. The data were differenced in order to see the small-scale spatial variations in the wind and to remove the mean wind motions. It is easy to see the short-period variation in the wind as measured by the nose boom wind sensor. For example, inspection of the lateral wind speed time history in Figure 3 shows an approximate 70 kts difference in the lateral (V) component between 100 and 125 seconds. Also easily seen are the wind gradients (difference between wing tip sensors), e.g., the variation in differences appears to be about ± 10 kts for the longitudinal and lateral, and a little more for the vertical. A presentation of the turbulence aspects of these data is given in reference 1.

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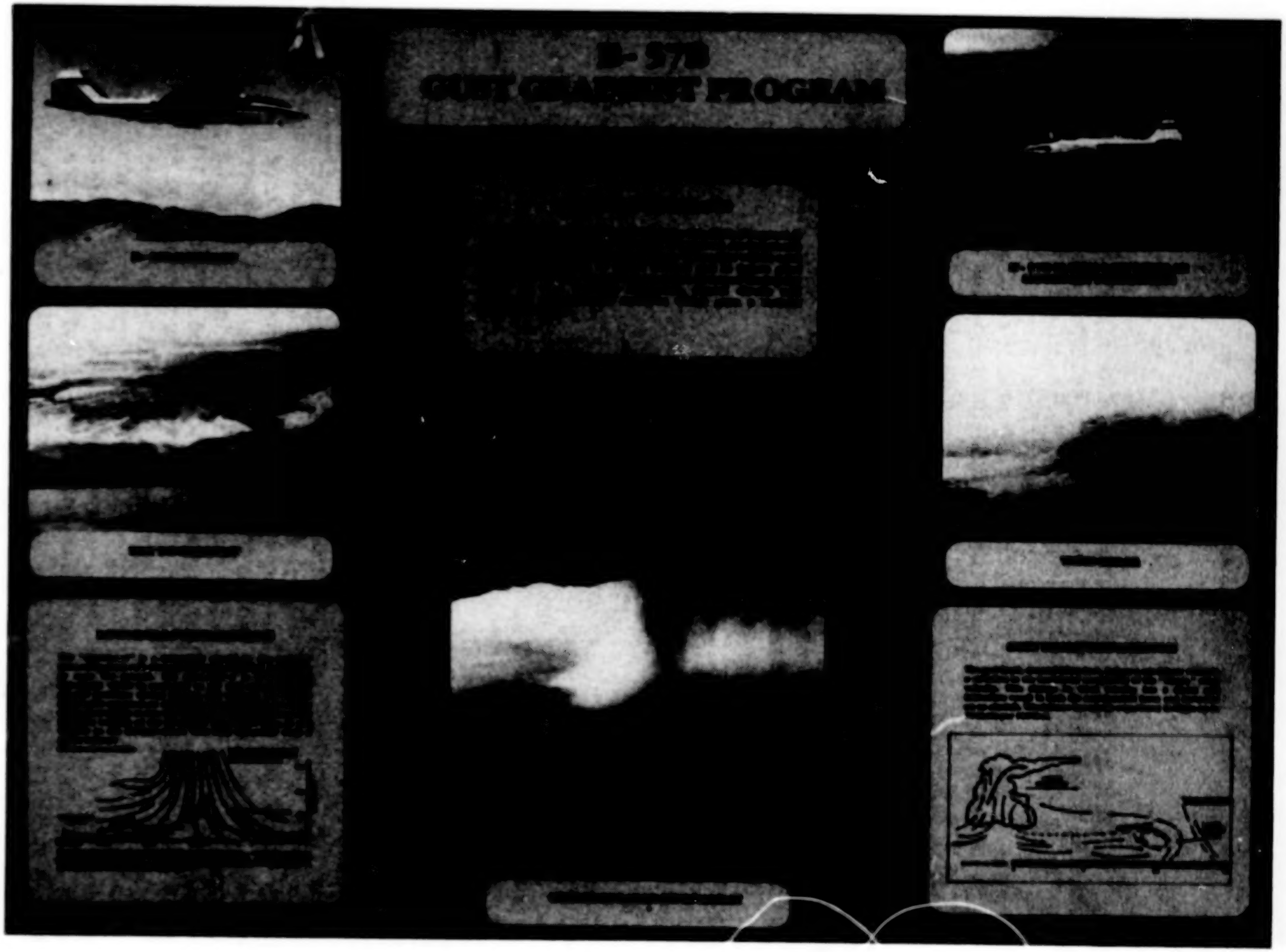
B-57B
GUST GRADIENT PROGRAM

Figure 1. B-57B Gust Gradient Program.

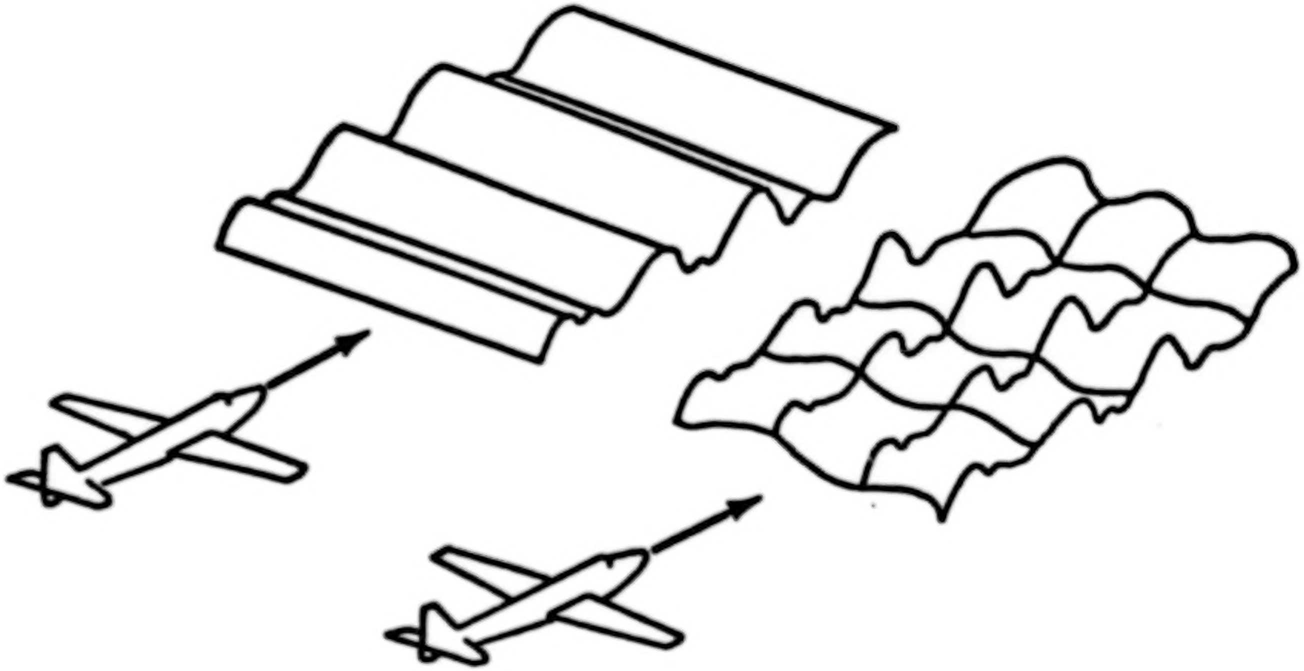

Figure 2. Assumption of Turbulence Models.

Table I. Program Status

- Status of Data Sets
  - 11 Joint JAWS, Denver
  - 3 NASA/Dryden, Edwards
  - 3 NASA/MSFC, Huntsville
  - 5 NSSL, Oklahoma City
  - 2 NASA/Dryden, Edwards
  - 7 Joint NASA/NOAA, Boulder
- Data Enhancement and Augmentation
  - Statistically significant data samples for approach and takeoff (similar to MSFC field test)
  - All weather capability for data gathering in wet environment and closer to storm centers
  - Small-scale wind and turbulence structure by flying paths in direct comparison with other instrumentation; i.e., Doppler radar, Doppler lidar, airborne lidar (Convair 990)
  - Data to supplement numerical forecasting models
- Tentative Plans
  - Participate in NSSL's 1985 Spring Storm Program
    - Low-level gust gradient data for a wet environment
    - Gust front as contrasted to microburst
    - Flights directly down radar beam
  - Joint effort with C-990 Airborne Lidar Field Program (winter '84-'85; Lone Pine, California)
    - Turbulence
      - Large scale -- lidar
      - Small scale -- B-57B
    - Altitude --2000 - 45,000 ft AGL
    - Data uses (B-57B):
      - Augment present gust gradient data
      - Verification of UDRI turbulence index relative to CAT location
      - Mountain waves (AGW) basic studies

Table II. Type of Data

Site	C	C_R	L	L_R	L-M	$(L-M)_R$	M	M_R	M-S	$(M-S)_R$	S	S_R
						TAKE-OFF						
Denver (JAWS)	18	0	9	1	1	0	4	0	1	0	0	0
DFRF	10	0	3	0	3	0	0	0	0	0	0	0
MSFC	2	0	0	0	0	0	0	0	0	0	0	0
OKC	0	0	8	1	0	0	0	0	0	0	0	0
Boulder	8	0	8	0	0	0	1	0	0	0	0	0
TOTAL	38	0	28	2	4	0	5	0	1	0	0	0
						LEVEL FLIGHT						
Denver (JAWS)	29	4	70	26	24	5	33	9	9	2	2	0
DFRF	8	0	20	0	10	0	20	0	1	0	14	0
MSFC*	24	0	0	0	0	0	0	0	0	0	0	0
OKC	21	4	13	11	2	1	0	1	0	0	0	0
Boulder	68	0	42	0	0	0	2	0	0	0	0	0
TOTAL	150	8	145	37	36	6	55	10	10	2	16	0
						LANDING						
Denver (JAWS)	19	0	7	2	1	0	4	0	1	0	0	0
DFRF	5	0	3	0	3	0	0	0	0	0	0	0
MSFC	10	0	0	0	0	0	0	0	0	0	0	0
OKC	5	0	7	3	2	0	0	0	0	0	0	0
Boulder	11	0	12	0	0	0	0	0	0	0	0	0
TOTAL	50	0	29	5	6	0	4	0	1	0	0	0

Nomenclature:
C - Calm or no indication
L - light turbulence
L-M - light to moderate turbulence
M - moderate turbulence
M-S - moderate to severe turbulence
S - severe turbulence
Sub R - indicates rain conditions

*5 tests flown in circles around MSFC's lidar.

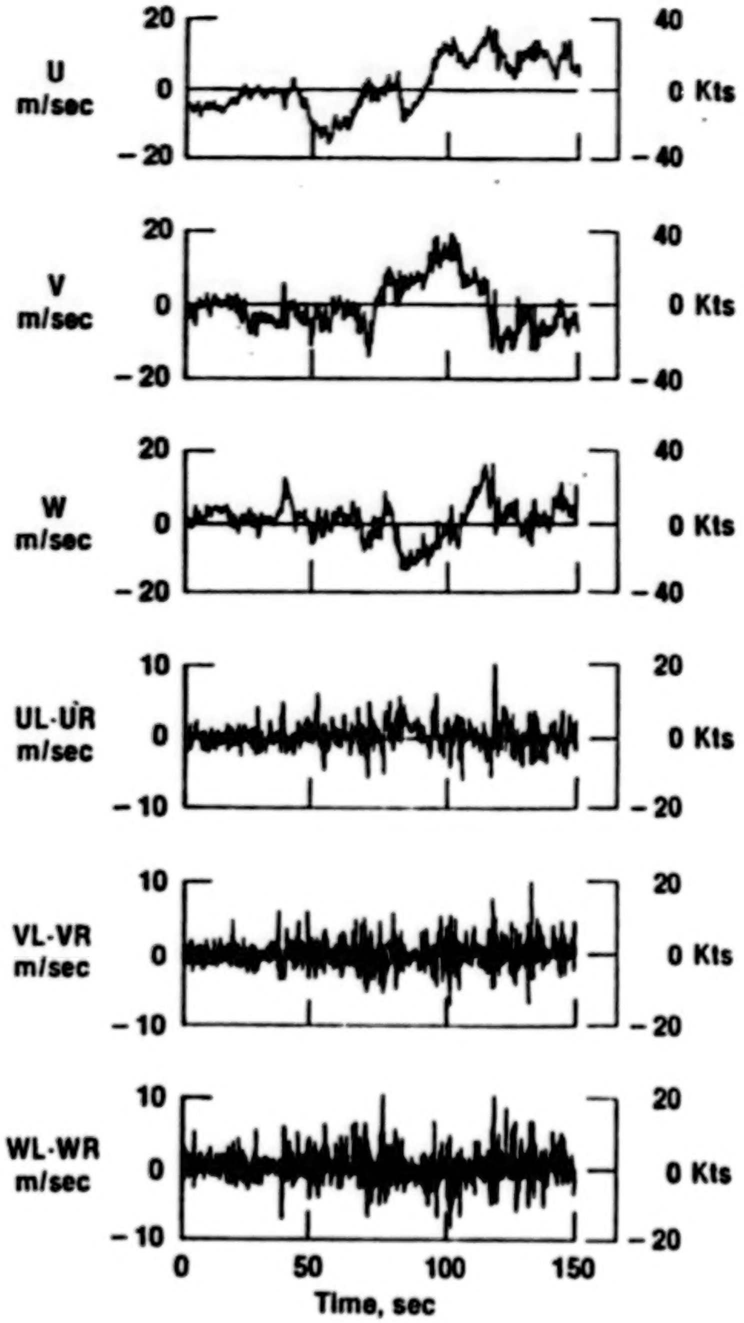

Figure 3. Plot of Gust Gradient Data from Flight 7, Run 10 on July 15, 1982, in the Denver, Colorado, area.

The data from NASA/MSFC was selected in order to do a comparative analysis of aircraft-measured data with Doppler lidar-measured data and also with data from a five-tower array at the MSFC. In collecting these data, the aircraft was flown on a 3° glide slope toward the lidar, while the lidar was sampling data along the same slope. The comparison of the aircraft and lidar data was very good. In fact, the quality of the comparison was such that additional data were desired and were collected at the Boulder, Colorado, tests using the NOAA lidar. The data comparing the aircraft-measured winds to tower-measured winds will be used to investigate the "frozen turbulence" theory of Taylor.

Figure 4 shows four frames from a film* which illustrates the wind variations over the airfoil of an aircraft. The film is an animation which illustrates the rolling and yawing of the aircraft as a result of the wind. For the purpose of the animation, roll and yaw were exaggerated by a factor of five, so that aircraft response to the encountered turbulence is easier to observe. The arrows represent the wind vectors. Changes in arrow length correspond to changes in speed, and the arrows point in the direction of the wind. The data for the movie was from a level flight (2,000 feet AGL) made at the JAWS on July 15, 1982. The aircraft was flying with an indicated airspeed of about 200 kts.

REFERENCE

1. Frost, Walter: Turbulence models. Wind Shear/Turbulence Inputs to Flight Simulation and Systems Certification, NASA CP-2474, 1987, pp. 125-149.

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* A copy of this film can be made available through ED42, NASA Marshall Space Flight Center, Marshall Space Flight Center, AL 35812.

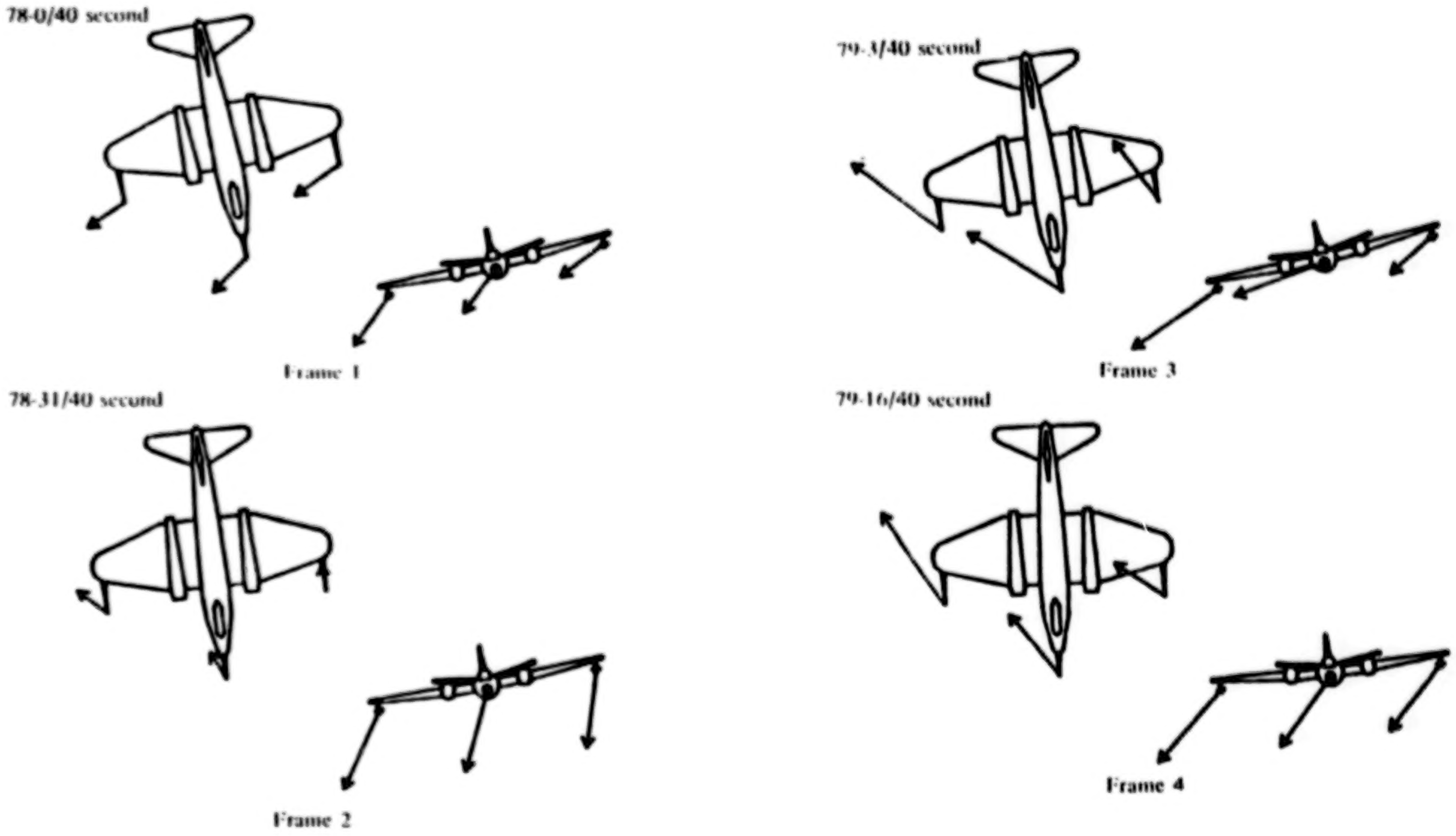
78-0/40 second
Frame 1
78-31/40 second
Frame 2
79-3/40 second
Frame 3
79-16/40 second
Frame 4

Figure 4. Illustration of Wind Velocities During the 78 Second of the Data Record.

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TURBULENCE MODELS

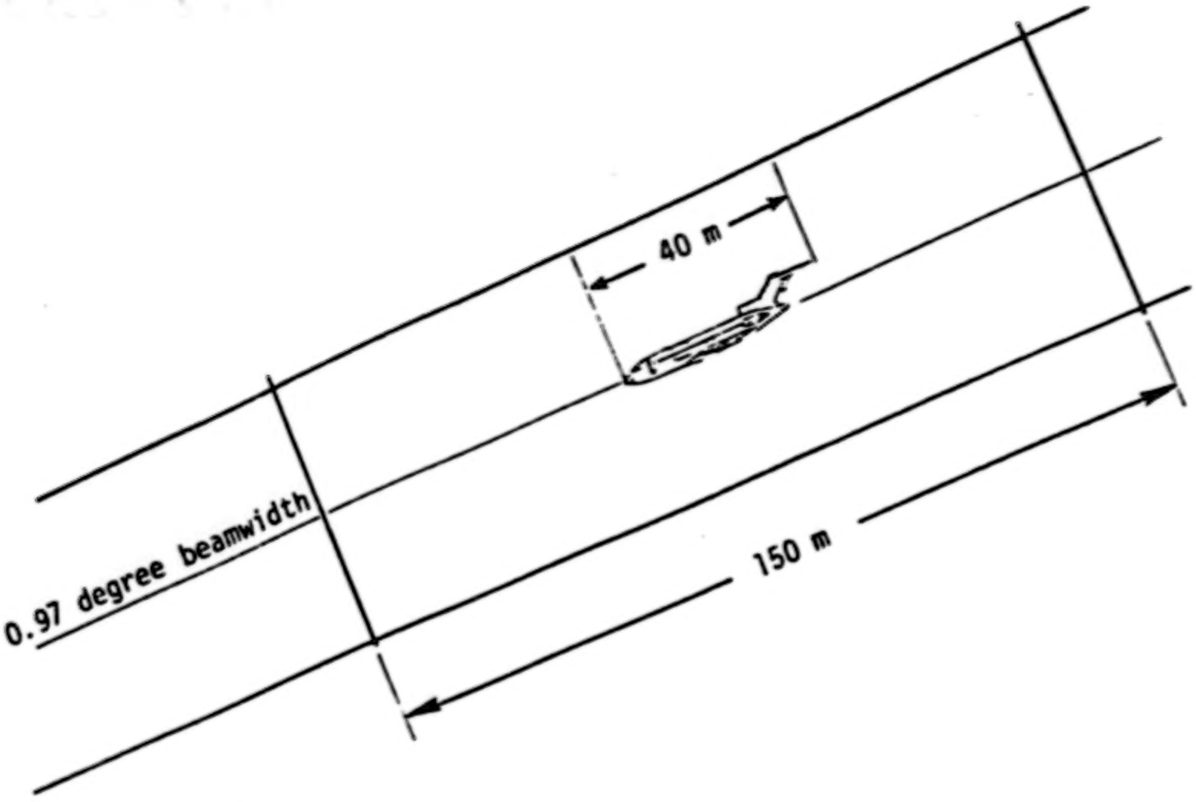
Walter Frost
FWG Associates, Inc.
Tullahoma, Tennessee

An example of the analyses of the B-57 Gust Gradient data for Flight 6, Run 3 is given in the appendix to this paper. This is the format in which the data will be available. For further details on the data, contact Dennis Camp at NASA Marshall Space Flight Center.

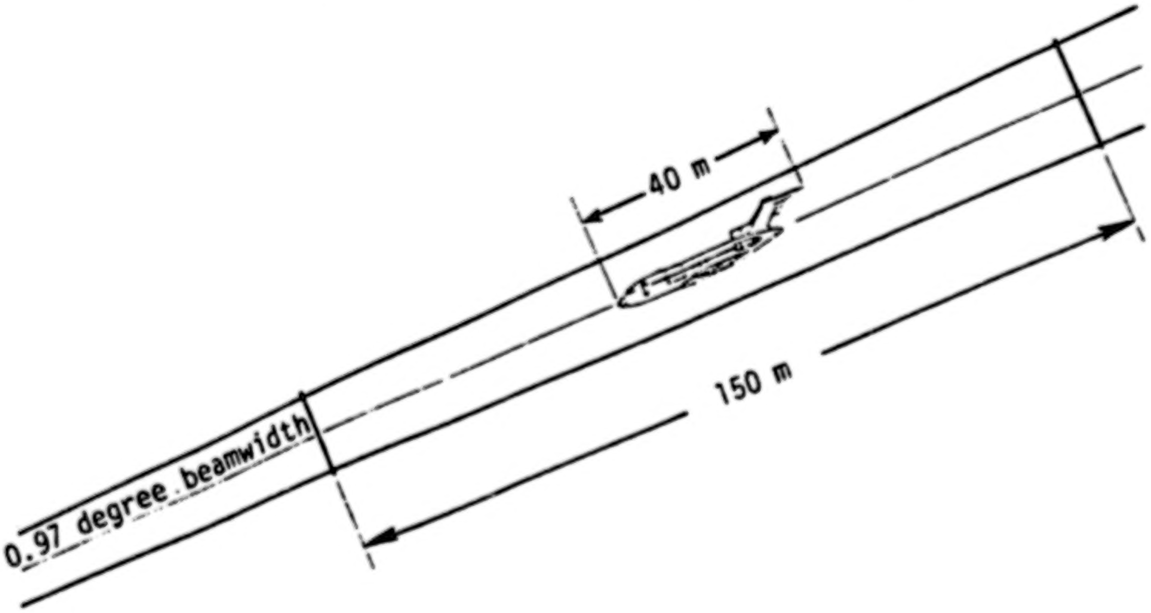
I would like to address the subject of modeling turbulence for use with the JAWS wind shear data sets. The present FAA AC 120-41 wind shear models (reference 1) are quasisteady wind models. FAA recommends superimposing upon these winds a Dryden spectrum model of turbulence. For the JAWS data, we have to decide whether this approach is adequate or whether we need to analyze and model turbulence differently.

The question is why do we need turbulence for the JAWS data set? In looking at scaled drawings of a B-727-type aircraft inside of a typical volume element of the size sensed by the Doppler radar (figure 1), the volume element is seen to engulf the airplane. A typical volume element or range gate probed by a Doppler radar is about 150 m in length and spreads out cylindrically with distance from the radar. Any atmospheric motion less than the volume element in size is averaged out of the radar signal. In addition, the data are transferred to a spatial grid that is about 200 m by 200 m. The 200 m grid size scaled relative to the dimensions fo various types of aircraft is shown in Figure 2. One observes that even the biggest airplane, the B-747, occupies only a small part of the volume element. Thus, there are atmospheric disturbances going on within the volume element that are relatively large compared to the aircraft, but that are smoothed out by the averaging process.

For discussion purposes, say that the typical grid scale for the JAWS data set is 200 m. The spatial sampling frequency is thus 1/200 m^{-1}. The Nyquist frequency is then 1/400 m^{-1}. Assuming an airspeed of 80 m/s, the temporal frequency is then approximately 0.2 Hz. This means that any disturbances less than the grid spacing in spatial scale, or higher than roughly 0.2 Hz frequency, is not contained in the JAWS data set. Figure 3 shows that the phugoid frequency is typically less than the 10^{-2} Hz, so most effects on the order of the phugoid frequency are contained in the JAWS data set. The short period frequency are between 10^{-2} and 0.5 Hz. Therefore, some short period disturbances are contained in the JAWS data. For simulation of structural effects, however, high-frequency turbulence must be superimposed upon the JAWS data. In Figure 3, the one-dimensional von Karman longitudinal θ_{11}, and lateral, θ_{22}, spectra are plotted along with the three-dimensional energy spectrum, E. It is observed that for very large length scales, there is not much turbulence energy beyond the JAWS cutoff frequency. The question is how to model turbulence contained in the higher frequency range.


40 m
0.97 degree beamwidth
150 m

a) Range gate at 150 m (490 ft) above runway


40 m
0.97 degree beamwidth
150 m

b) Range gate at 50 m (160 ft) above runway

Figure 1. Approximate size of B-727-100 type aircraft relative to a range gate volume element.

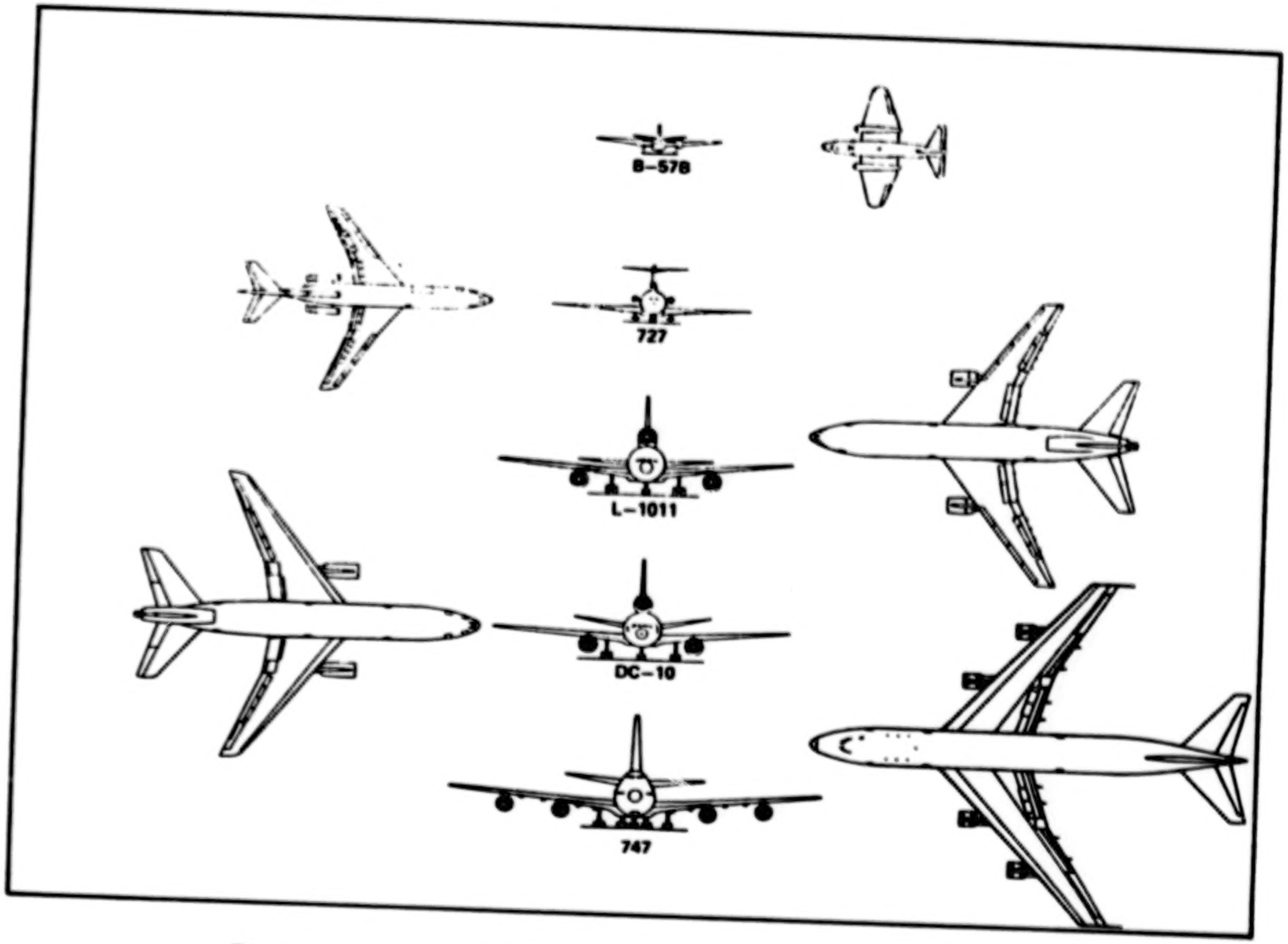

B-57B
727
L-1011
DC-10
747

Figure 2. Comparison of JAWS sizes of July 14 grid size with various size aircraft.

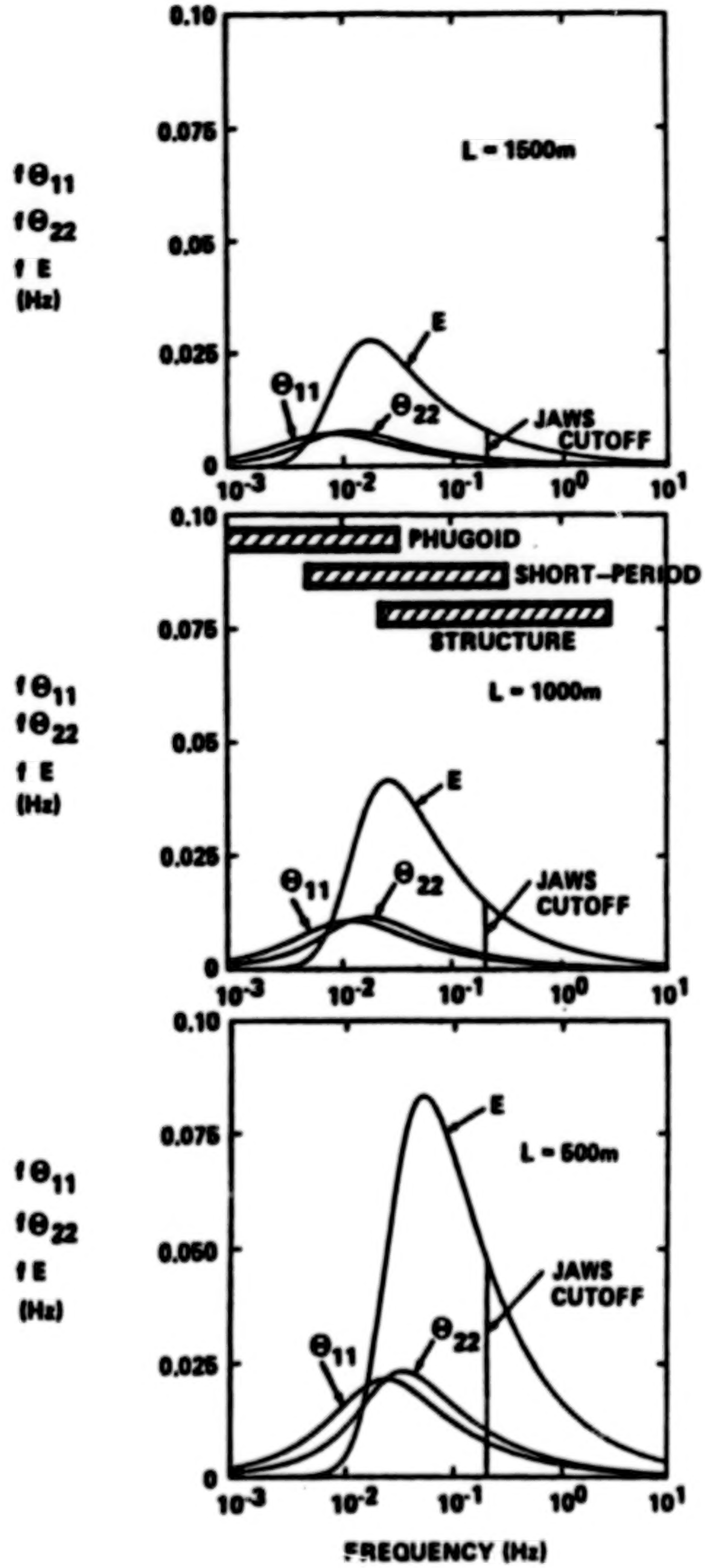


Figure 3. Comparison of significant frequencies with JAWS cutoff frequency.

The effect of turbulence is not likely to appreciably influence the trajectory of the aircraft; however, it may have appreciable effect on handling qualities and pilot workload.

Typically, turbulence models use the point mass assumption that the aircraft is totally immersed in the turbulence. The point mass assumption is sometimes enhanced by assuming a linear gradient of gust velocities. This sometimes leads people to believe that the linear gradients of the JAWS data are also included in their wind shear models. The two gradient terms are different things, however, as will be described later. Also models have been developed which provide spanwise gust gradients across the airfoil. These could be used in simulation but are relatively complex mathematical models and are not likely in use at this time. Warren Campbell at Marshall Space Flight Center has proposed a three-dimensional turbulence model (reference 2).

The conventional method of simulating turbulence is to pass a computer-gererated Gaussian white noise through a filter. The filter shapes the random output signal such that it has certain statistical properties characteristic of the atmospheric turbulence to be simulated. Generally, the two statistical parameters which are reporduced are the turbulence intensity and the frequency content through the turbulence energy spectrum. The Dryden spectrum is most commonly used. It is well established that the von Karman spectrum fits the turbulence experimental atmospheric data better than the Dryden spectrum; however, the Dryden is much easier to handle mathematically. Typically, the output of a turbulence simulation results in a Gaussian distribution of the velocity fluctuations. Again, it is well established that atmospheric turbulence is not Gaussian; however, this approximation is generally acceptable. Turbulence simulation models exist that will provide non-Gaussian turbulence, but they are mathematically complex. Thus, simulated turbulence with Gaussian velocity distribution, Dryden spectra, and specified turbulence intensity is universally used because it is the simplest to implement. This simple model provides the three fluctuating velocity components and treats the airplane as a point mass. Figure 4 illustrates schematically, however, that the point mass model inherently treats only one-dimensional wind variation in the flight direction.

As the figure further illustrates, however, turbulence is typically three-dimensional. To account for spatial variation in turbulence, several turbulence modelers have gone to the idea of linear gust gradients. The typical parameters entering the turbulence models are shown in Figure 5. The turbulence model provides the uniform gust W_x, W_y, W_z and linear gradients of gust velocity p_g, q_g, and r_g. These gradient terms create rolling, pitching and yawing moments. It should be noted, however, that these terms are different from the wind shear terms discussed earlier. The effect is very similar but the gradient values are of defferent magnitudes. Moreover, if you turn off the turbulence simulation, the effects of the linear gradient terms will disappear. The flow chart for computing random turbulence with linear gust gradients is shown in Figure 6. The question is whether turbulence generated in this manner should be superimposed on the JAWS wind fields and, if so, how turbulence of the same scale length, which already exists in the JAWS data, is to be filtered out.

Another issue relative to turbulence simulation is whether to generate the turbulent wind fluctuations in the body frame or the earth frame of reference. If you consider only the translational velocity (i.e., w_x, w_y, w_z) components and

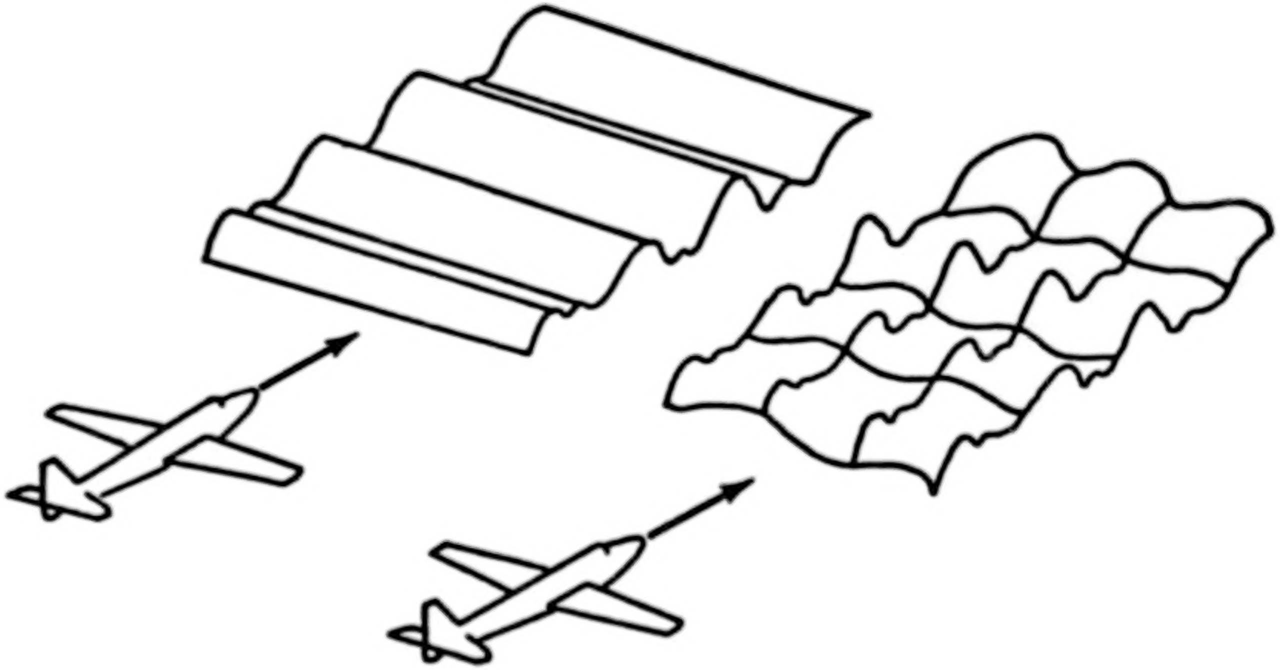


Figure 4. Assumptions of turbulence simulation.

- Uniform Gust Immersion

  w_x, w_y, w_z

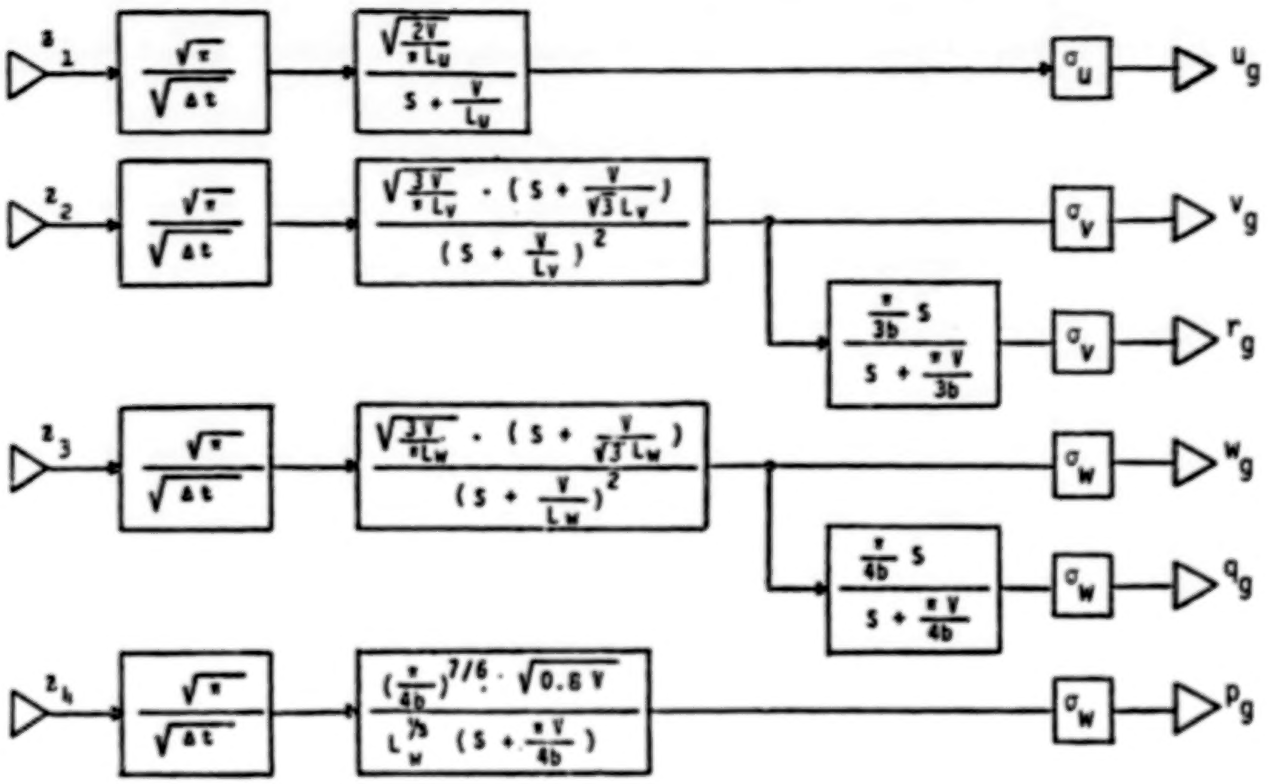
- Linear Gradients of Gust Velocities

$$p_g = -\frac{\partial w_z}{\partial y}$$

$$q_g = \frac{\partial w_z}{\partial x} = -\dot{\alpha}_g$$

$$r_g = -\frac{\partial w_y}{\partial x} = \dot{\beta}_g$$

Figure 5. Parameters from turbulence models with distributions of gusts over aircraft (from MIL-F-8785B, reference 3).


z_1
$\frac{\sqrt{\pi}}{\sqrt{\Delta t}}$
$\frac{\sqrt{\frac{2V}{\pi L_u}}}{s + \frac{V}{L_u}}$
σ_u
u_g
z_2
$\frac{\sqrt{\pi}}{\sqrt{\Delta t}}$
$\frac{\sqrt{\frac{3V}{\pi L_v}} \cdot (s + \frac{V}{\sqrt{3} L_v})}{(s + \frac{V}{L_v})^2}$
σ_v
v_g
$\frac{\frac{\pi}{3b} s}{s + \frac{\pi V}{3b}}$
σ_v
r_g
z_3
$\frac{\sqrt{\pi}}{\sqrt{\Delta t}}$
$\frac{\sqrt{\frac{3V}{\pi L_w}} \cdot (s + \frac{V}{\sqrt{3} L_w})}{(s + \frac{V}{L_w})^2}$
σ_w
w_g
$\frac{\frac{\pi}{4b} s}{s + \frac{\pi V}{4b}}$
σ_w
q_g
z_4
$\frac{\sqrt{\pi}}{\sqrt{\Delta t}}$
$\frac{(\frac{\pi}{4b})^{7/6} \cdot \sqrt{0.8 V}}{L_w^{1/3} (s + \frac{\pi V}{4b})}$
σ_w
p_g

z_i = independent, digital, Gaussian, unit RMS white noise

Figure 6. Random turbulence simulation with linear gust gradients.

generate these in the earth coordinate system based on appropriate wind models, add them to the mean winds or quasi-steady winds, and transfer the total wind speed components back to the body axis, you should have no trouble. Now consider the rotational turbulence componens shwon in Figure 6, p_g, q_g, and r_g. In computing these components, you must be careful. If a spectrum for turbulence gradients is used (see Figure 6) then your analysis will depend upon how it was measured. Since q_g and r_g are correlated with w_g and v_g, respectively, the w_g and v_g components must be obtained by transforming from the earth frame of generation to the body frame before q_g and r_g are computed.

Figure 4 clearly indicates that the turbulence is not uniform over the airfoil although the basic models currently in use make this assumption. Some attempts at modeling spanwise gust variation have been investigated. One approach is illustrated in Figure 7. Basically, this approach consists of calculating the lift as a function of time by using the indicial function n(y,t). The indicial function gives the lift response of the wing due to a sinusoidal gust occurring at position y along the wing, and at corresponding time, t. After carrying out the operations shown in Figure 7, you end up with the spectrum of the lift. The expression of the spectrum of the lift, however, contains the cross-correlation or two-point spectrum. This is normally developed assuming isotropic homogenous turbulence. The reason for the NASA B-57 Gust Gradient Program is to provide additional information relative to the two-point spectrum or distribution of gusts acress the airfoil. By using the spectrum of lift to model your filter and passing a white noise through this filter, you can generate a random lift with gust variations across the wing as a function of time. Similar approaches could be made for rolling moments, yawing moments, etc. This approach is very time consuming, however, and I do not believe that it is used in any operational flight simulator at present. Moreover, the spectrum is not only a function of the wind or atmospheric conditions, but also of the airplane dynamics, or of n(y,t), which is the lift characteristic of the airfoil.

A second approach to incorporate spanwise turbulence gradients is to utilize the gust gradient data with strip theory. The previous model, of course, is also based upon strip theory; but in the approach addressed here, finite elements are used and the assumption of isotropic homogeneous turbulence eliminated. Figure 8 shows how the wind is distributed across the airfoil. The velocity at each element varies with time. Thus, at any incident of time, we have a random distribution of the wind which is used to calculate the lift by the straightforward strip theory approach. With the gust gradient data, we have divided the wing into three panels using the measured relative wind speeds at both wing tips and at the nose boom to calculate the lift. With this approach, we have calculated yawing and rolling moments which the aircraft experienced during a data gathering flight based on the measured values. The results show that the yawing and rolling moments can be quite high due to the non-uniform wind distribution. We are streamlining this approach for simulator applications. The results would give us teh rolling and yawing moments caused by turbulence of a smaller scale than that included in the JAWS data sets. Basically, what we are doing at this time is utilizing the test flight data. The relative wind, speed, and angle of attack are input to the strip theory computer program, and lift, drag, yaw, and roll moments are computed. These values are then input into the aerodynamic forces in our six-degree-of-freedom aircraft motion computer program, and the flight path is calculated. The results are then compared with the actual measured aircraft performance to determine how valid is the strip theory computational procedure. There is always a

$$L(t) = \int_{-\infty}^{\infty} \int_{-b/2}^{b/2} h(t,y) w_z(V(t - t_1), y) dy dt_1$$

Assume

$$h(t,y) = h_t(t) h_y(y)$$

$$\phi_L(\omega) = |H_t(\omega)|^2 \phi_{w_{ze}}(\omega)$$

$$\phi_{w_{ze}} = \frac{1}{b} \int_0^b \Gamma(\eta) \tilde{\phi}_{w_z}(\omega, \eta) d\eta$$

where

$$\tilde{\phi}_{w_z}(\omega, \eta) = \frac{1}{V} \int_{-\infty}^{\infty} e^{-i\omega\xi/V} \psi_{w_z}(\sqrt{\xi^2 + \eta^2}) d\xi$$

Figure 7. Spectral method for spanwise gust variation.

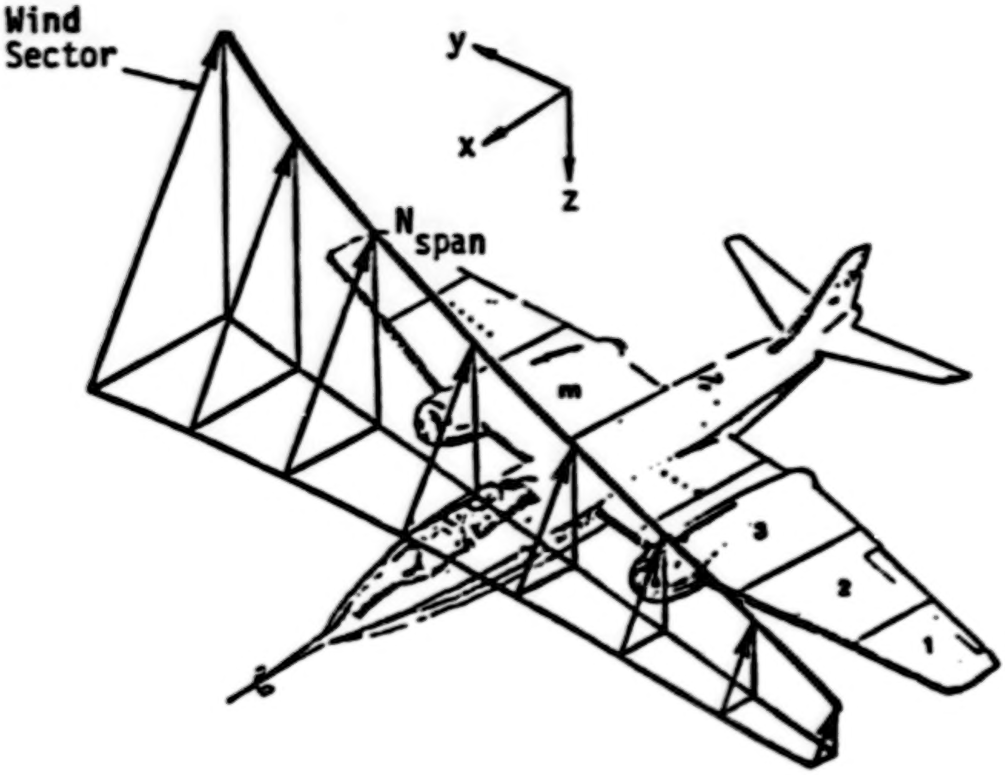

Wind Sector
y
x
z
N_{span}
m
3
2
1

Figure 8. Gust variation over the wing span using finite elements.

$$u_i(X,Y,Z,t) = \bar{U}_i(X,Y,Z,t) + \sigma_i(X,Y,Z,t)*W_i(X,Y,Z)$$

$u_i(X,Y,Z,t)$ ARE THE SIMULATED WINDS
$\bar{U}_i(X,Y,Z,t)$ ARE THE ENSEMBLE AVERAGE WINDS
$\sigma_i(X,Y,Z,t)$ ARE THE ENSEMBLE AVERAGE GUST INTENSITIES
$W_i(X,Y,Z)$ IS "FROZEN" TURBULENCE

ADVANTAGES

* 3–D TURBULENCE AND GUST GRADIENTS
* COMPATIBILITY WITH DOPPLER RADAR DATA
* ABILITY TO SIMULATE A WIDE RANGE OF ATMOSPHERIC PHENOMENA

DISADVANTAGES

* REQUIREMENT FOR A LARGE DATA BASE
* 1–D SPECTRA ARE NOT AS ACCURATE AS FOR A 1–D SIMULATION

Figure 9. Three-dimensional turbulation simulation.

problem of control inputs in making such a comparison. The gust gradient aircraft has now been equipped with control input measuring devices, and hence, we can make comparisons of computed control inputs relative to actual control inputs by the pilot. On a statistical basis, we are getting excellent agreement between the measured and computed results. The development of this system for utilization in operational flight simulators will provide more realistic simulation of roll and yaw motions.

A final model of turbulence proposed for imposing the small scales of turbulent motion into the JAWS data sets is a three-dimensional turbulence model developed by Warren Campbell (reference 2). The concept inputs three-dimensional white noise into a filter. The filter is a three-dimensional spectrum model which can be either the von Karman or the Dryden spectrum. Campbell utilizes the von Karman spectra, which results in homogeneous isotropic turbulence, but fully three-dimensional. Application of the model to the JAWS data is based on establishing a smaller grid within each grid element of the JAWS data set. As an illustration, Campbell has utilized 10 m grid spacings for his turbulence model (within the 200 m by 200 m JAWS grid, you impose internally a 10 m by 10 m grid). Turbulence, which Campbell refers to as frozen (i.e., not varying with time, but varying spatially) is computed for each grid point within the large JAWS grid volume element.

Figure 9 illustrates the three-dimensional turbulence simulation concept. The quantity σ_i is the turbulence intensity which can vary spatially. This value is unknown and must be determined experimentally. Analysis of the Doppler radar second moment is being carried out to determine if these values of the turbulence intensity can be determined. From the preliminary results, it is clear that the turbulence intensity will vary appreciably around the downdraft section of the flow and probably behave similarly to other turbulence models far from the center of the downdraft. The nature of turbulence associated with a microburst and its determination from the existing JAWS data are issues which we may wish to address in the discussion sessions.

Returning to the issue of what turbulence to superimpose on the JAWS data, a number of models are available as described, (see Figure 10). There are two extremes, and probably somewhere in between is a good solution. The simple model is the Gaussian Dryden spectrum model; again, we know is not correct, but is easy to use mathematically, and most simulators probably have this system already incorporated.

One of the problems, however, in using any turbulence model to superimpose on the wind shear data is that the JAWS data already incorporates considerable low-frequency turbulence. Therefore, the low frequency must be filtered out of the superimposed turbulence generated by a model which will contain all frequencies. The question is how is this best done? One approach is simply to run the simulated turbulence through a filter that cuts out everything that is less than 200 m in scale.

An alternate approach is to use a highly complex model such as Campbell's model. Here you generate blocks of turbulence which are input to the JAWS data set and you fly through these moving the blocks as you proceed. There are a couple of problems, however: one is realistic values of the turbulence intensity which, hopefully, we can get from the JAWS Doppler radar second moment data. The second problem is length scale. The question is what scale of turbulence does

- Simple Model -- FAA AC No. 120-41
  - Dryden spectra
  - Intensities and length scale are functions of altitude
- Highly Complex Model -- Campbell's 3-D
  - Homogeneous isotropic
  - Incorporate all correlations
  - Blocks stacked within JAWS grid volume

Figure 10. Possible turbulence models for JAWS data set.

one utilize in the simulation model? We do not have a good handle on length scales for turbulence associated with a microburst. Thus, a number of questions remain unanswered relative to developing a turbulence model to superimpose upon the quasi-steady JAWS data winds.

The conclusions, then, are as follows. 1) Turbulence of length scales less than the JAWS grid size should be superimposed on wind fields to provide correct simulation of pilot workload. Also, to correctly simulate the short-period aircraft response as well as structural response, this smaller scale turbulence is necessary. 2) To develop a realistic and effective turbulence model, research is required. The research should address the interpretation of turbulence intensity and information relative to turbulence length scale from Doppler radar second moments. How to establish a meaningful length scale is a major issue which must be addressed from a research point of view. Finally, a research study to investigate the trade-off between degrees of complexity in models and computer capabilities as well as the fidelity of the models is required.

REFERENCES

1. Criteria for Operational Approval of Airborne Wind Shear Alerting and Flight Guidance Systems. Advisory Circular 120-41, Federal Aviation Administration, November 1983.

2. Campbell, Warren C.: A Spatial Model of Wind Shear and Turbulence for Flight Simulation. NASA TP-2313, 1984.

3. Military Specification - Flying Qualities of Piloted Airplanes. MIL-F-8785C, November 5, 1980.

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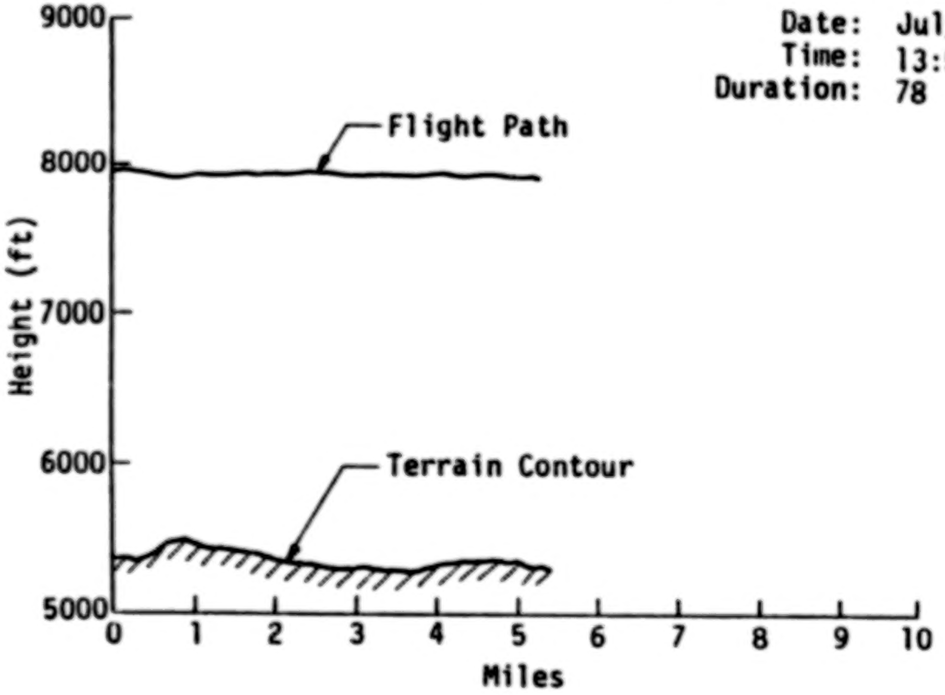
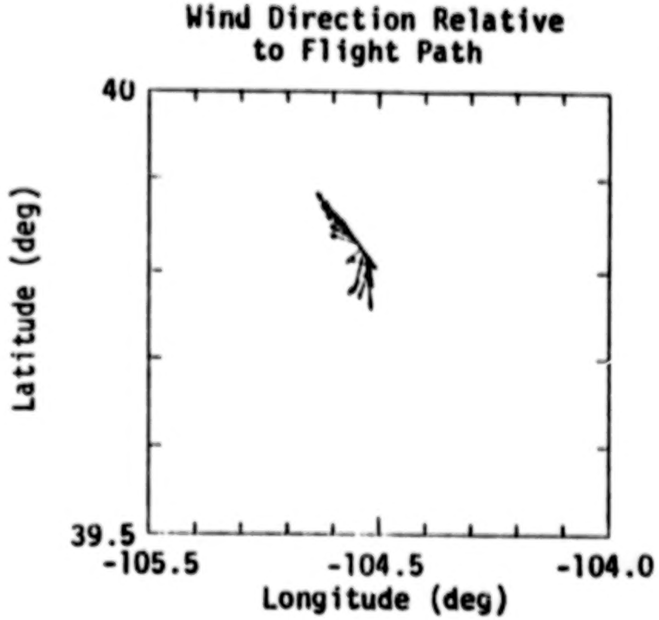
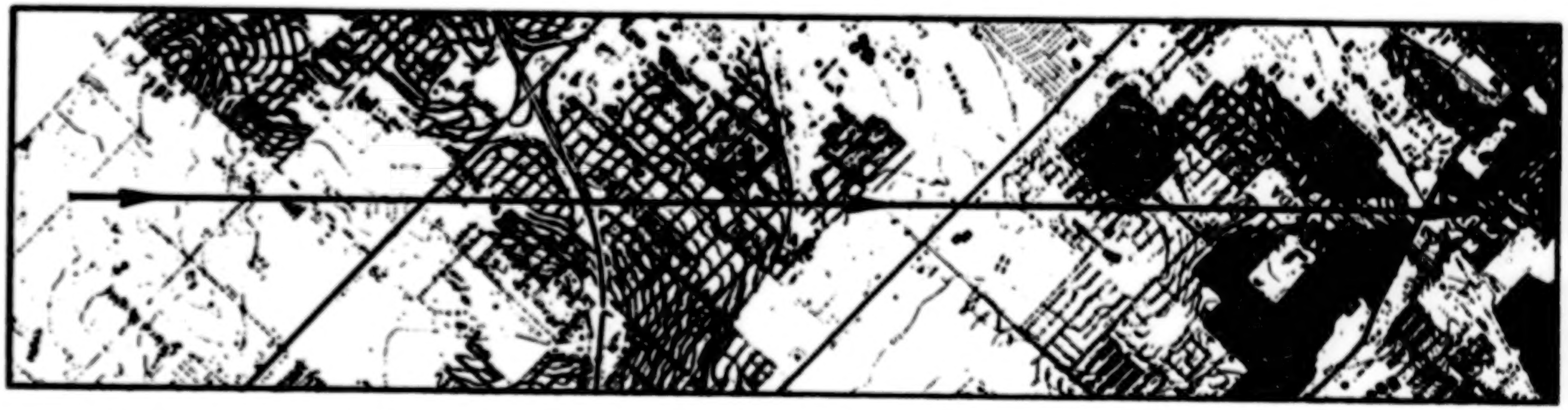
FLIGHT PATH INFORMATION: FLIGHT 6, RUN 3

Date: July 14, 1982
Time: 13:50:05
Duration: 78







AVERAGE PARAMETERS

Flight 6, Run 3, JULY 14, 1982

I. Mean Airspeed (m/s)

V_L	V_C	V_R
111.5	110.7	112.4

II. Standard Deviation of Gust Velocities (m/s)

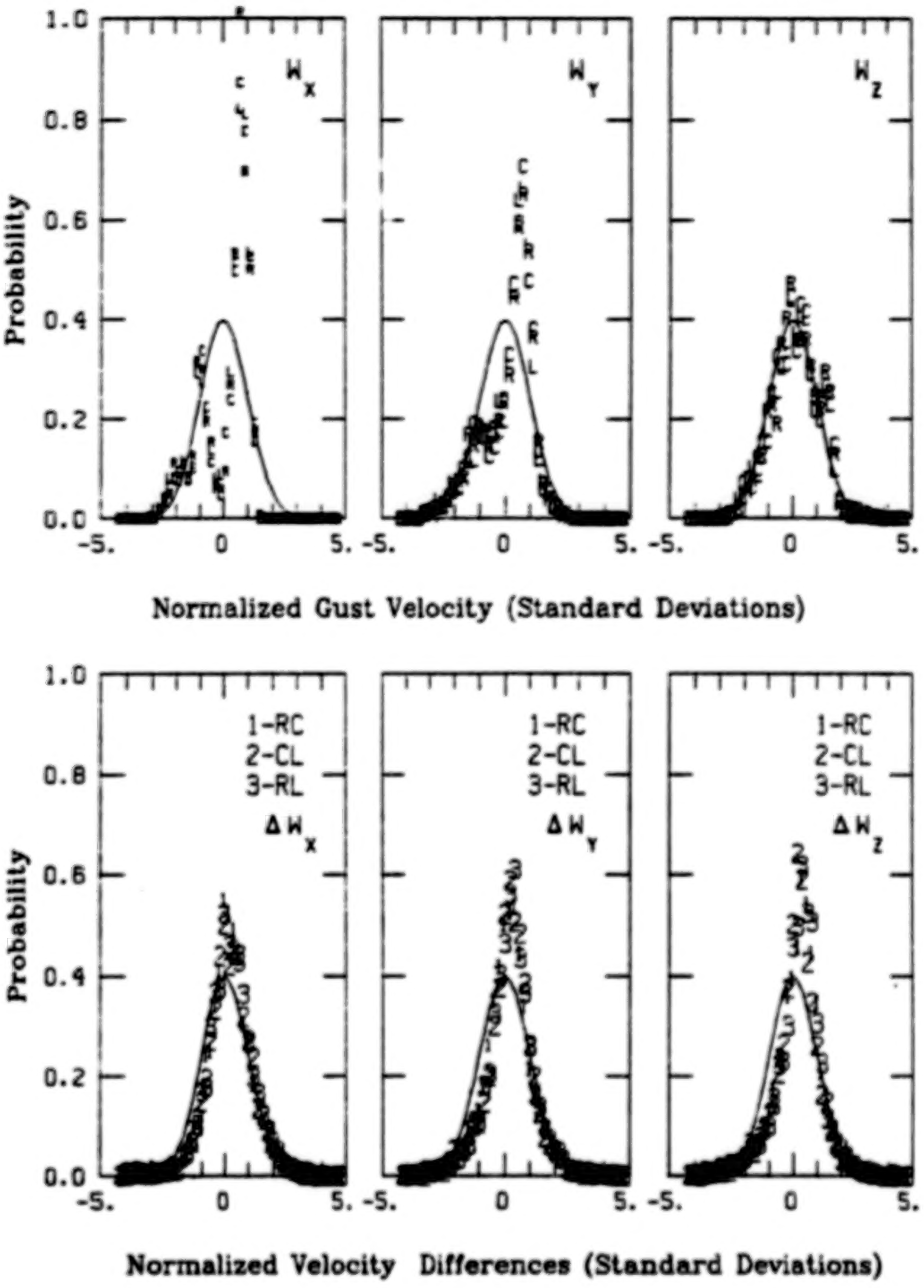
$\sigma_{w_{XL}}$	$\sigma_{w_{XC}}$	$\sigma_{w_{XR}}$
3.75	3.68	3.73
$\sigma_{w_{YL}}$	$\sigma_{w_{YC}}$	$\sigma_{w_{YR}}$
1.77	1.81	1.73
$\sigma_{w_{ZL}}$	$\sigma_{w_{ZC}}$	$\sigma_{w_{ZR}}$
2.10	2.04	2.24

III. Standard Deviation of Gust Velocity Differences (m/s)

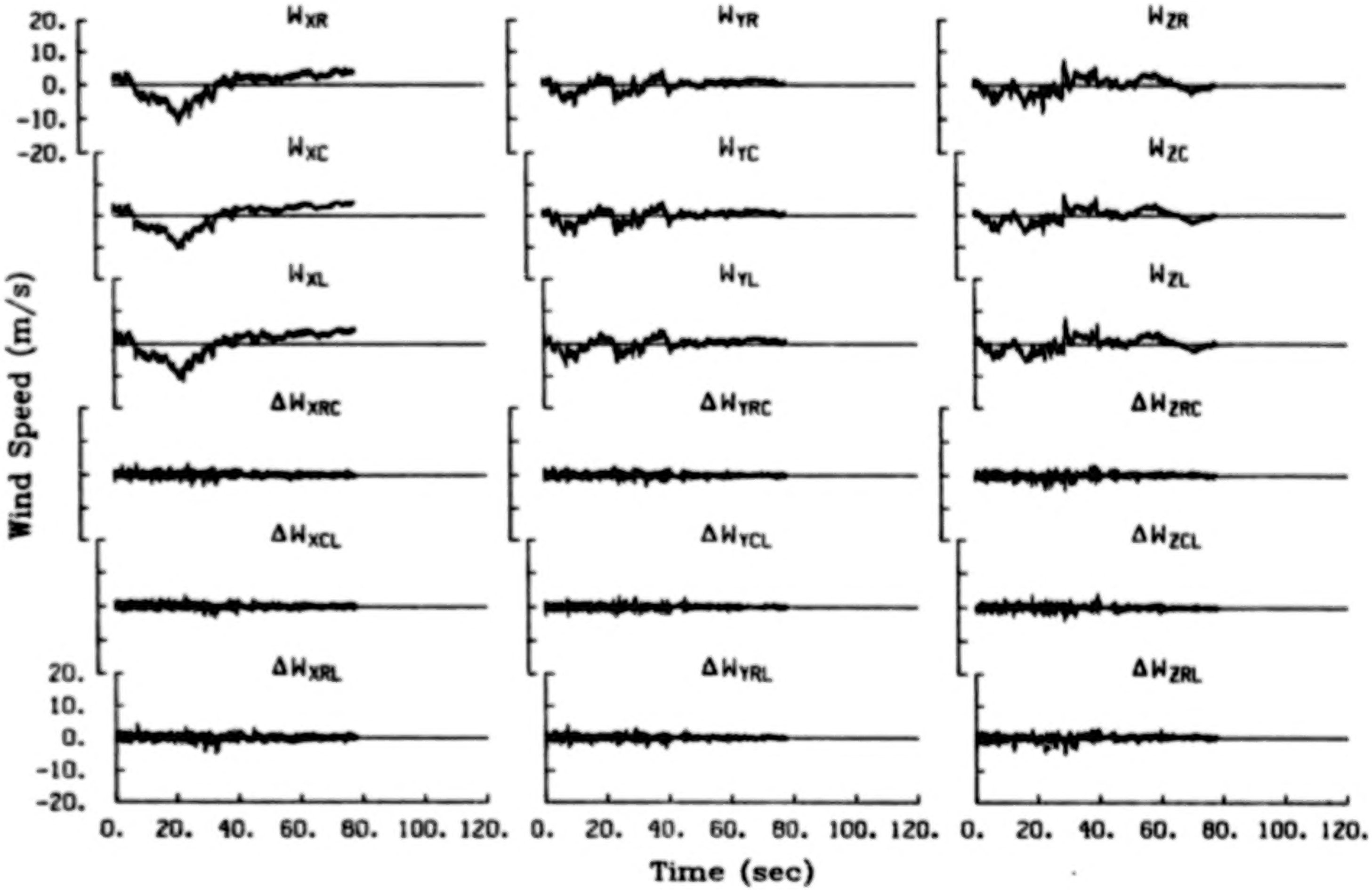
$\sigma_{\Delta w_{XCL}}$	$\sigma_{\Delta w_{XRC}}$	$\sigma_{\Delta w_{XRL}}$
0.64	0.65	0.82
$\sigma_{\Delta w_{YCL}}$	$\sigma_{\Delta w_{YRC}}$	$\sigma_{\Delta w_{YRL}}$
0.60	0.59	0.65
$\sigma_{\Delta w_{XCL}}$	$\sigma_{\Delta w_{ZRC}}$	$\sigma_{\Delta w_{ZRL}}$
0.66	0.72	0.83

IV. Integral Length Scale (m).

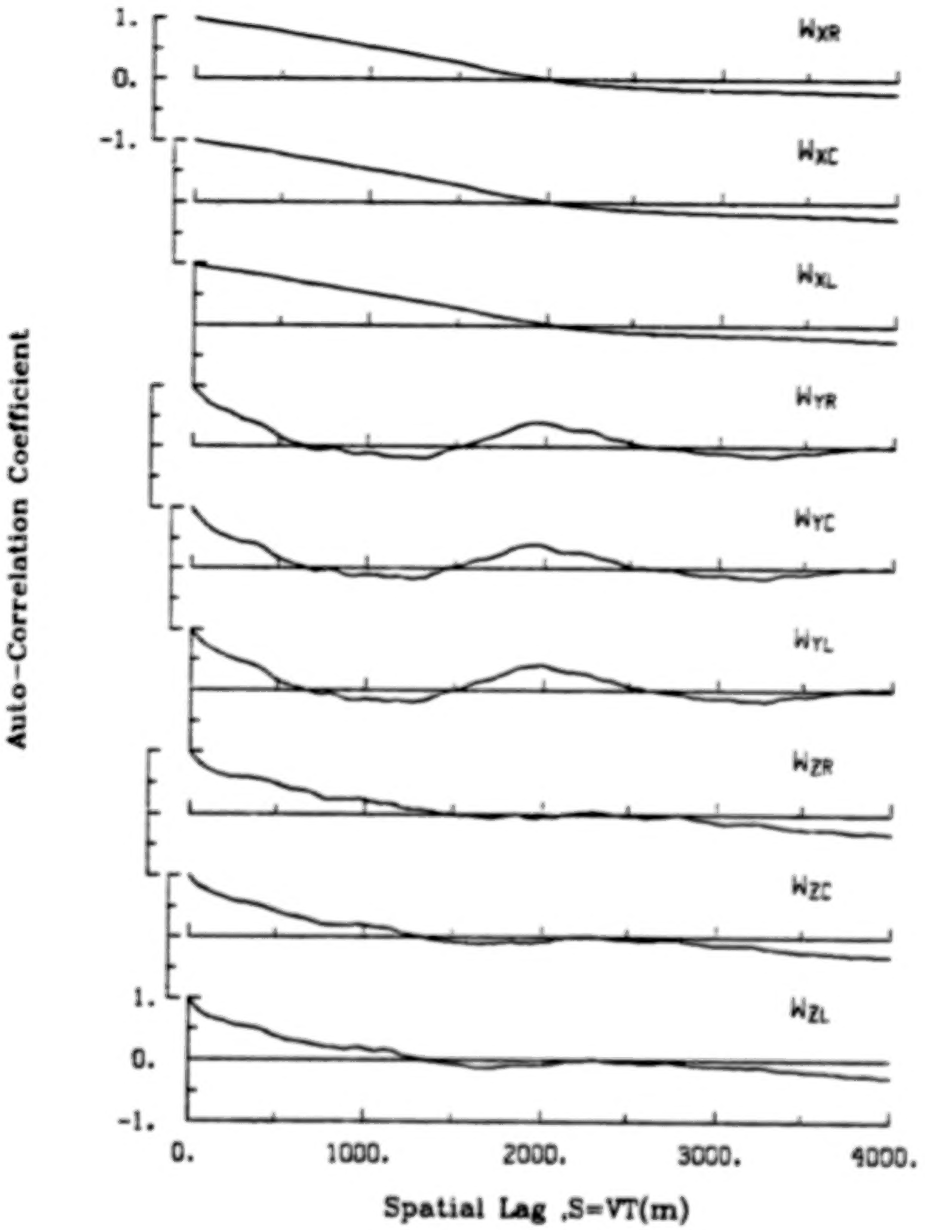
$L_{w_{XL}}$	$L_{w_{XC}}$	$L_{w_{XR}}$
1042	1043	1038
$L_{w_{YL}}$	$L_{w_{YC}}$	$L_{w_{YR}}$
554	541	559
$L_{w_{ZL}}$	$L_{w_{ZC}}$	$L_{w_{ZR}}$
940	976	1050



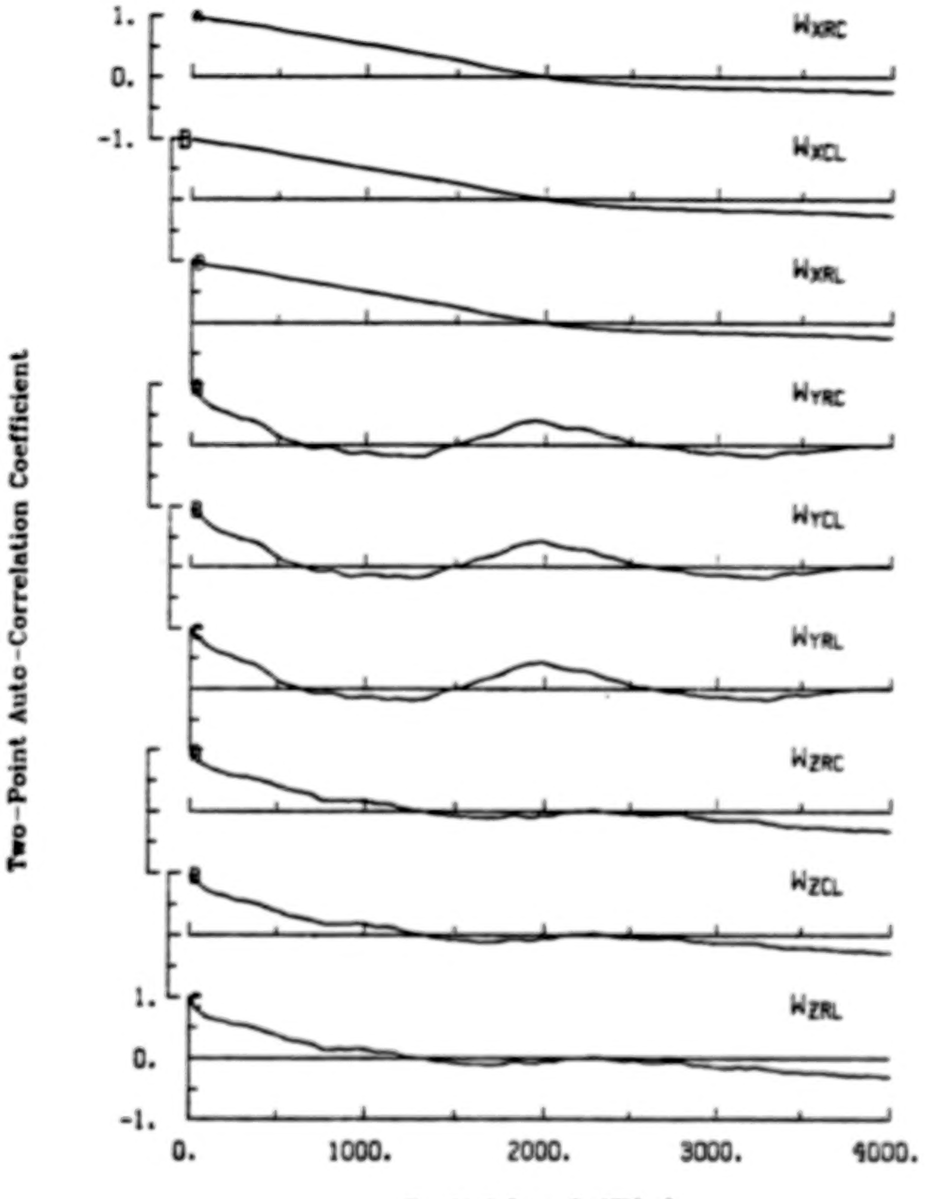
PROBABILITY DENSITY FUNCTION FOR GUST VELOCITIES AND THEIR DIFFERENCES. R= right , C= center , L= left , Flight 6, Run 3.



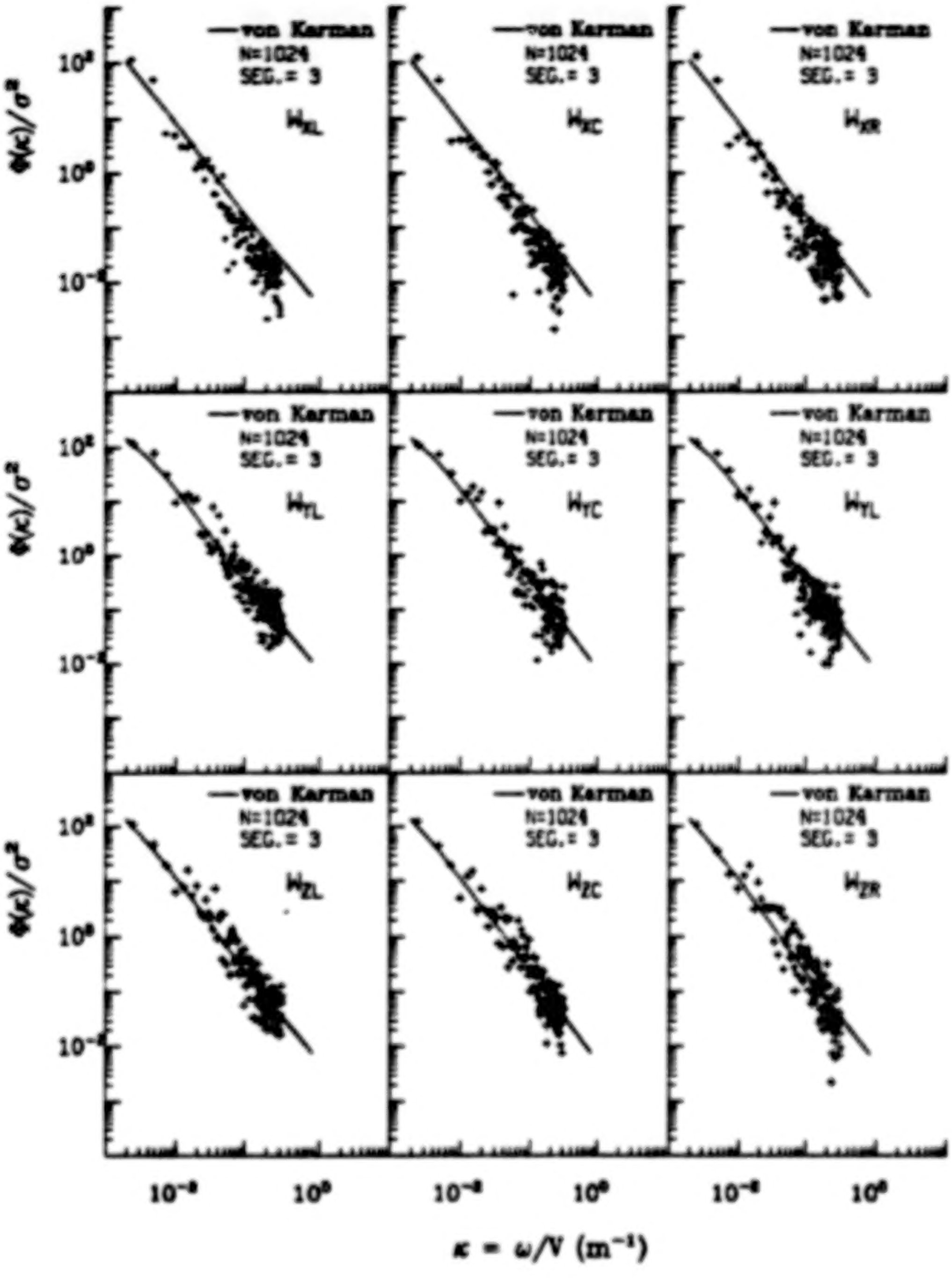
TIME HISTORIES OF THE GUST VELOCITIES AND THEIR DIFFERENCES,
Flight 6, Run 3.



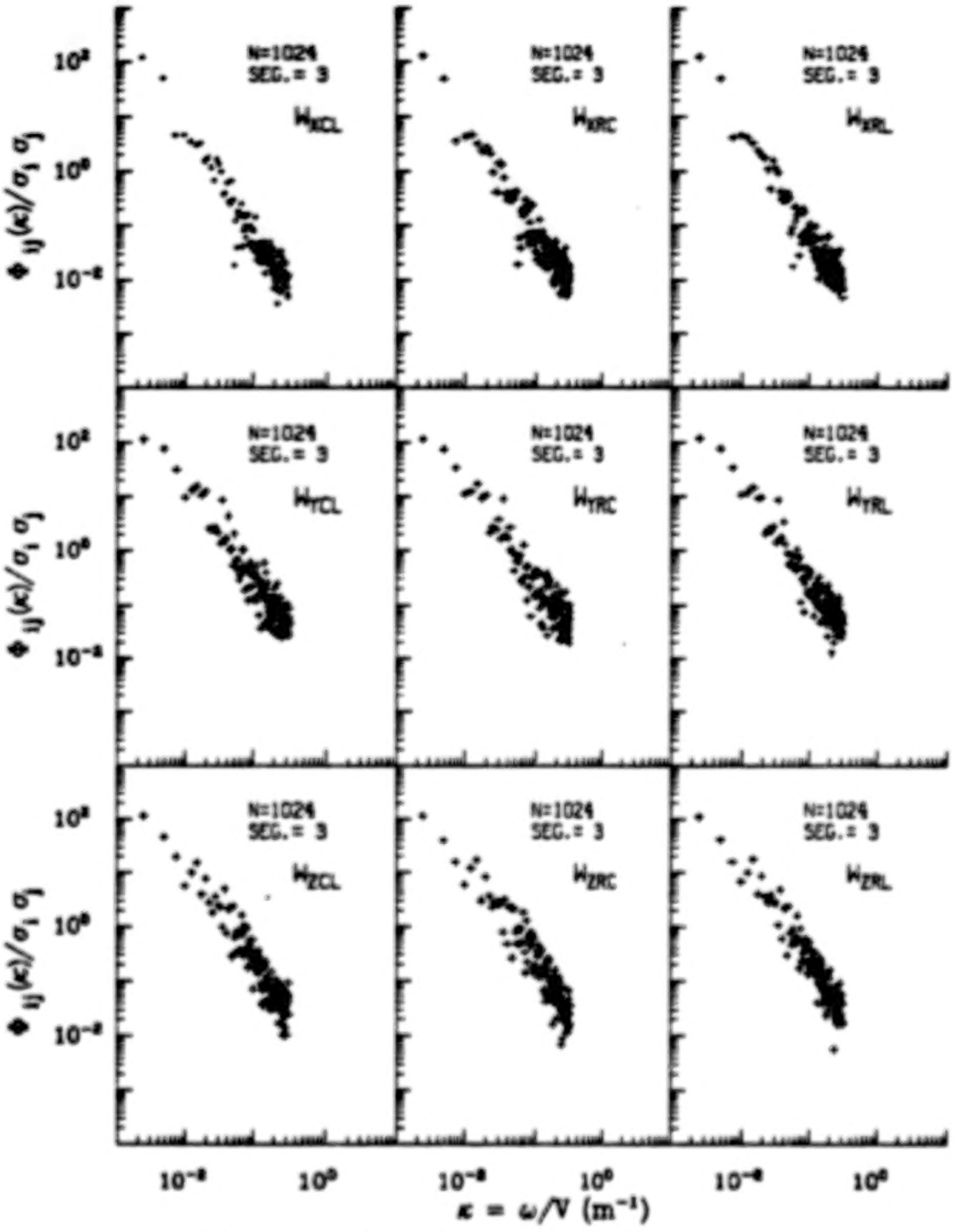
SINGLE-POINT AUTO-CORRELATION OF GUST VELOCITIES.
Flight 6, Run 3.



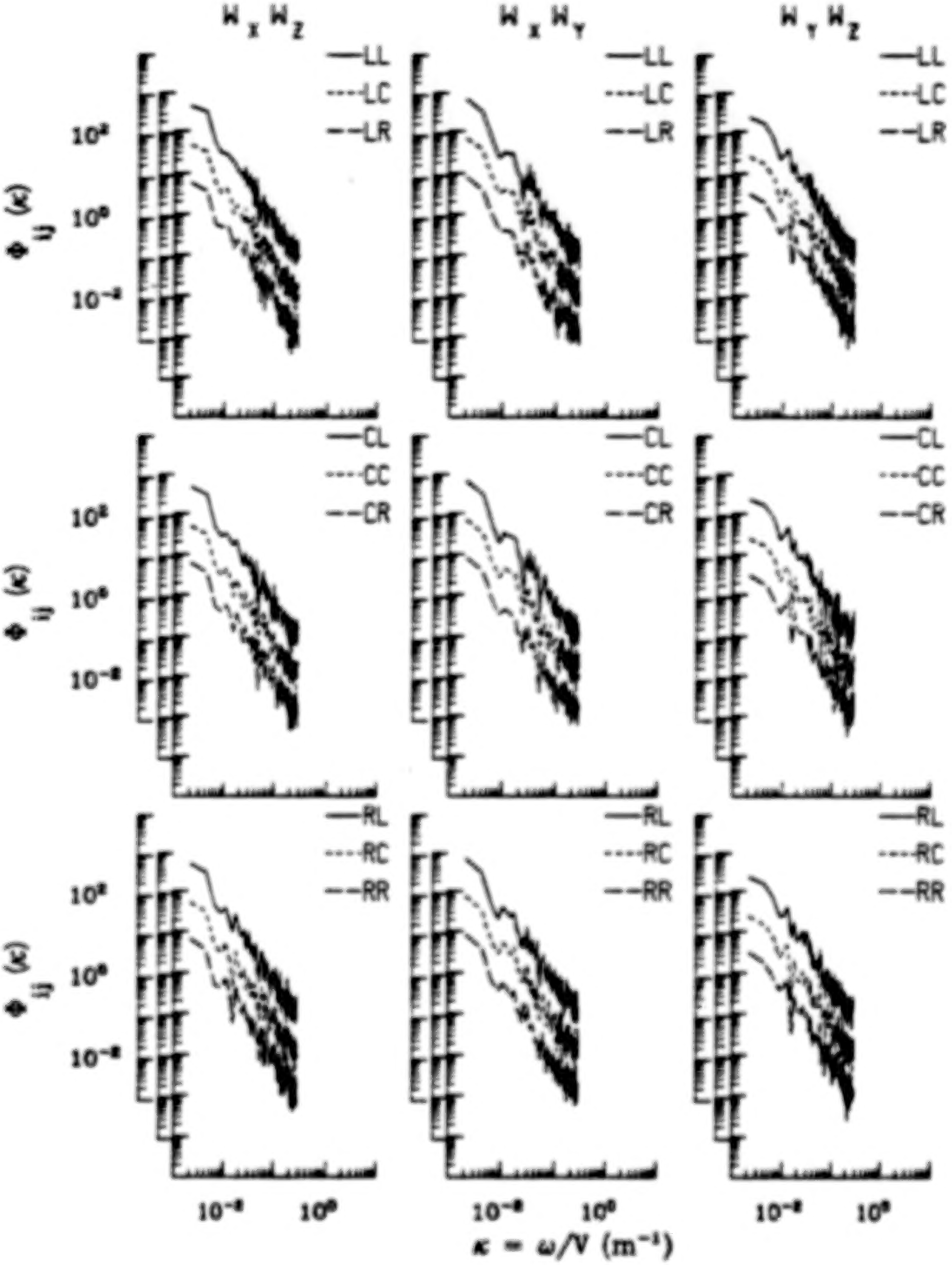
TWO-POINT AUTO-CORRELATION COEFFICIENT
lines computed from Taylor s hypothesis, A and B spatial correlation between center and wing tips, C spatial correlation between wing tips,
Flight 6, Run 3.



NORMALIZED AUTO-SPECTRA OF GUST VELOCITIES, Flight 6, Run 3.



NORMALIZED TWO-POINT AUTO-SPECTRA OF GUST VELOCITIES, Flight 6, Run 3.



TWO–POINT CROSS–SPECTRA OF THE GUST VELOCITIES, Flight 6, Run 3.

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RANGE OF ALL PARAMETERS MEASURED
Flight 6, Run 3

START TIME = 49805.4844 STOP TIME = 49883.5094

CHANNEL	UNITS	HIGH	LOW	MEAN	RMS	POINTS
2 PHI DOT	RAD/SEC	.072	-.088	-.00324	.02078	3121
3 ACCL N CG	G UNITS	1.627	.642	.99422	.99850	3121
4 THETA DOT	RAD/SEC	.037	-.045	.00481	.01095	3121
5 THETA	RAD	.094	.031	.06292	.06434	3121
6 PHI	RAD	.041	-.069	-.00889	.02096	3121
7 PSI 1	DEGREES	313.321	308.297	310.69637	310.69764	3121
8 DEL PSI 1	DEGREES	2.904	-1.857	.51978	1.02301	3121
9 PSI 2	DEGREES	314.988	310.080	312.55654	312.55775	3121
10 DEL PSI 2	DEGREES	2.874	-1.802	.51022	1.01485	3121
11 ACCL N LT	G UNITS	2.020	.160	1.01168	1.02621	3121
12 ACCL N RT	G UNITS	1.859	.182	1.02835	1.04275	3121
13 ACCL X CG	GUNITS	.139	.032	.06434	.06518	3121
14 ACCL Y CG	G UNITS	.175	-.159	.00796	.05271	3121
15 ALPHA CTR	RAD	.058	-.054	-.01058	.01490	3121
16 BETA CTR	RAD	.036	-.072	-.02107	.02740	3121
17 TEMP I	DEG F	107.798	106.899	107.33032	107.33056	3121
18 TEMP P	DEG F	90.006	89.647	89.83471	89.83472	3121
19 ACCL Z INS	G UNITS	1.633	.620	1.00459	1.00892	3121
20 ALPHA RT	RAD	.068	-.060	-.00229	.01282	3121
21 BETA RT	RAD	.063	-.035	.01447	.02156	3121
22 ALPHA LT	RAD	.069	-.039	.00071	.01119	3121
23 BETA LT	RAD	.021	-.085	-.02642	.03106	3121
24 PSI DOT	RAD/SEC	.035	-.027	.00346	.01146	3121
25 TEMP TOT	DEG C	29.514	28.240	28.94907	28.95259	3121
26 QC LT	PSID	.975	.758	.82327	.82447	3121
27 QC CTR	PSID	.944	.751	.81163	.81273	3121
26 QC RT	PSID	.993	.763	.83729	.83843	3121
29 PS	PSIA	10.979	10.680	10.95411	10.95412	3121
30 TEMP IRT	DEG C	24.966	13.439	20.73977	20.83180	3121
31 D TO G	METERS	8742922.214	8737460.433	************	************	3121
32 B TO D	DEGREES	80.291	80.229	80.26050	80.26050	3121
33 LONG	DEGREES	-105.006	-105.082	-105.04370	105.04370	3121
34 LAT	DEGREES	39.858	39.804	39.83064	39.83064	3121
35 TRK ANG	DEGREES	313.111	311.510	312.08458	312.08480	3121
36 HDG	RADIANS	5.496	5.410	5.45239	5.45241	3121
37 VE	M/SEC	-82.071	-85.818	-84.17617	84.18227	3121
38 VN	M/SEC	78.414	73.974	76.04477	76.05794	3121
39 ALTITUDE	KM	2.612	2.392	2.41049	2.41049	3121
40 TEMPC	DEGREES C	23.458	22.310	22.84278	22.84376	3121
41 EW WND SPD	KNOTS	9.351	-16.032	-7.78967	9.22385	3121
42 NS WND SPD	KNOTS	7.154	-17.897	-.60240	6.27648	3121
43 WIND SPEED	KNOTS	18.503	2.391	10.84520	11.15677	3121
44 WIND DIREC	DEGREES	359.998	.072	105.75741	129.53243	3121
45 AIRSPEED R	M/SEC	122.176	107.549	112.42393	112.45570	3121
46 AIRSPEED C	M/SEC	119.203	106.668	110.73093	110.76639	3121
47 AIRSPEED L	M/SEC	121.133	107.221	111.49930	111.53747	3121
48 DELTA ALT	METERS	195.070	-24.882	-6.41525	8.34510	3121
49 INRTL DISP	METERS	0.000	-15.034	-5.23568	6.53721	3121
50 UG RIGHT	M/SEC	5.250	-11.902	-.00000	3.73122	3121
51 UG CENTER	M/SEC	4.576	-10.520	-.00000	3.68761	3121
52 UG LEFT	M/SEC	4.812	-11.826	-.00000	3.75082	3121
53 VG RIGHT	M/SEC	4.611	-6.089	-.01278	1.71976	3121
54 VG CENTER	M/SEC	4.474	-6.336	-.01492	1.79824	3121
55 VG LEFT	M/SEC	4.239	-7.339	-.01482	1.76225	3121
56 WG RIGHT	M/SEC	7.622	-8.356	-.04249	2.22740	3121
57 WG CENTER	M/SEC	6.933	-6.061	-.03757	2.03396	3121
58 WG LEFT	M/SEC	8.091	-5.981	-.03986	2.09167	3121

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MICROBURST MODEL REQUIREMENTS FOR FLIGHT SIMULATION--
AN AIRFRAME MANUFACTURER'S PERSPECTIVE

Richard L. Schoenman
Boeing Commercial Airplane Company

ABSTRACT

A brief outline is given of topics for presentation and discussion at this workshop. As manufacturers and certifiers of transport airplanes and associated on-board systems, we have an interest in the prevention of wind shear-related accidents and incidents. Our near-term objectives are to provide our customers technical support in the areas of training as well as to research existing and potentially improved on-board systems. In the future, we expect to be implementing many improved systems. This will require certification as well as further educational activity in the use of these new systems.

What we need to achieve our objectives is a set of wind models for design work which characterize a wide variety of real microbursts as measured during the JAWS Project. The wind models should be limited in both size and complexity to just those features which degrade aircraft performance.

INTRODUCTION

The committee on Low-Altitude Wind Shear and Its Hazard to Aviation, sponsored by the National Research Council and directed by Terms of Public Law 97-369, has recently issued its findings (reference 1).

A number of recommendations were made, two of which relate to wind shear detection and guidance systems.

1. "The FAA should sponsor a program to develop and define standardized models of wind shear based on meteorological data."
2. "On-board sensors and guidance aids should be evaluated in a systematic manner to determine their merits for future development and for possible retrofit in existing aircraft."

We, as manufacturers and certifiers of the airplane systems, need to develop a methodology for quantitatively evaluating on-board alert and guidance systems. The training community must also develop techniques to traverse wind shear encounters with the existing fleet of airplanes. This paper addresses the data requirements for the former, although it may be that similar models will be required by the training community. The need of the training community is best expressed by those individuals directly involved in pilot training.

The "theoretical wind shear model" is an important element in determining aircraft performance in a wind shear as well as designing for effective operation of on-board alert and guidance systems, autopilots, flight directors, and autothrottles. While it is important to understand the effects of aircraft behavior

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for a broad spectrum of meteorological phenomena; i.e., microbursts, thunderstorms, gust fronts, mountain waves, etc.), it is our opinion that the most immediate need is for data to characterize the microbursts of limited geometrical size in the take-off and landing domain, close to the ground.

Analysis results to date indicate that three parameters characterizing microbursts can be used in preliminary evaluations of airplane performance. These parameters are: 1) the shear rate in knots/mile; 2) the total shear in knots; and 3) the value of the maximum downdraft velocity. This limited characterization assumes a linear shear rate and that the maximum downdraft velocity occurs as the transition is made from a head wind to a tail wind. While this simple model may be satisfactory for airplane performance and crew training applications, it is probably not accurate enough for wind shear alert and guidance system evaluations. Three-dimensional, symmetrical models with associated turbulence need to be developed for this purpose.

BOEING OBJECTIVES OF WORKSHOP PARTICIPATION (Figure 1)

- Microburst Mathematical Representation
  - To obtain a set of theoretical microburst models which reflect characteristics of the measured data
  - To establish whether the JAWS data base represents a wide variety of wind shears by comparison with other statistical studies (references 2 and 3).
- Statistical Analysis
  - To reconcile microburst math modeling theory with experiment using the JAWS data base.
  - Using the three parameters--the shear rate in knots per mile, the total shear in knots, and the value of the maximum downdraft velocity--establish frequency distribution diagrams from the JAWS data base. Determine whether parameters can be combined (which might be called the "total wind shear threat").

REQUIREMENTS RELATIVE TO WIND SHEAR AND TURBULENCE

- Summarize on-going programs requiring wind shear and turbulence data sets and models
  - Our on-going requirements are best summed up by three broad aims:
    - Wind shear training.
    - Accident/incident analysis.
    - System performance evaluation in wind shear, including existing and future systems. Examples are autoland performance, alert evaluation and guidance system development.

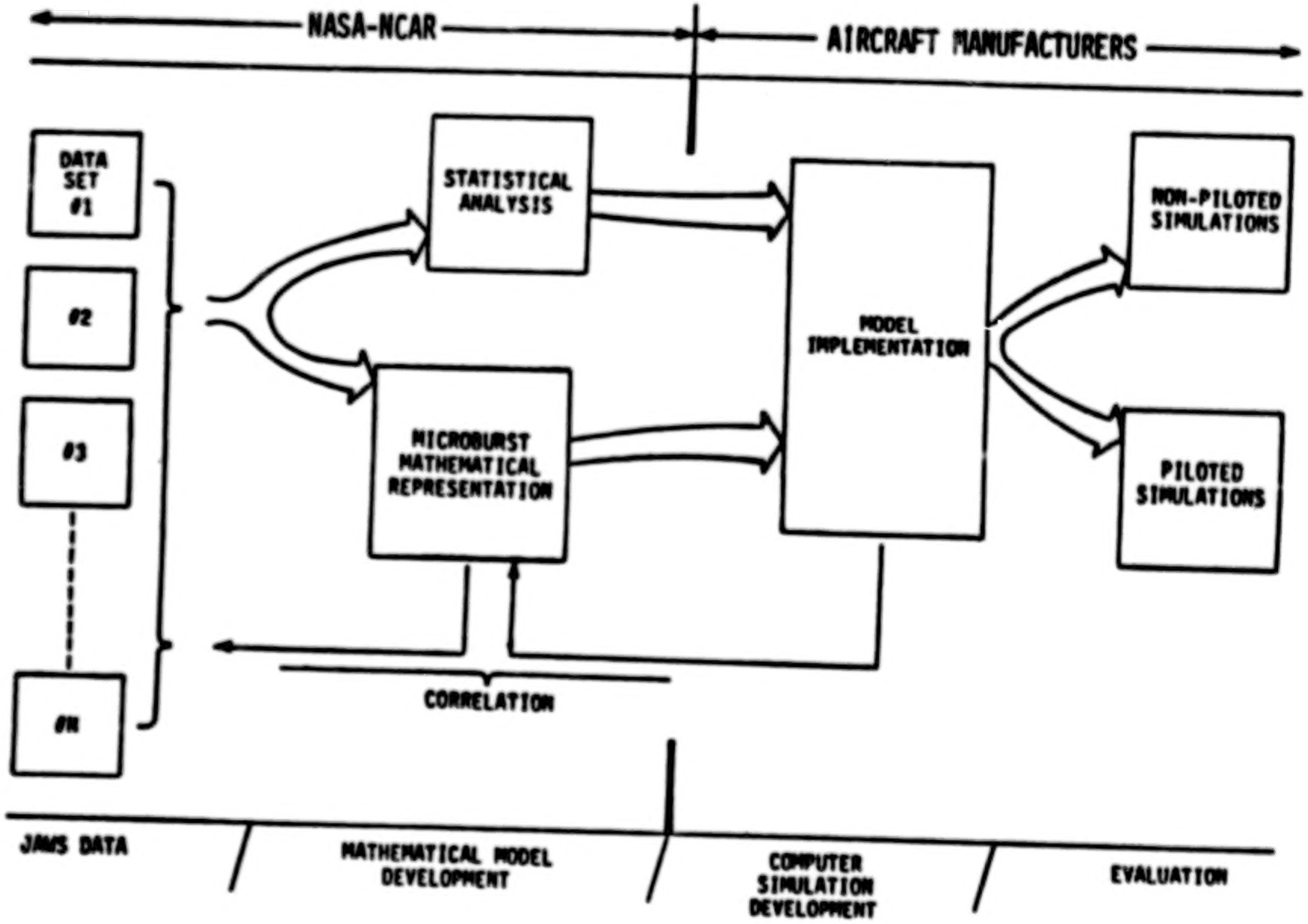

NASA-NCAR
AIRCRAFT MANUFACTURERS
DATA SET #1
#2
#3
#n
STATISTICAL ANALYSIS
MICROBURST MATHEMATICAL REPRESENTATION
MODEL IMPLEMENTATION
NON-PILOTED SIMULATIONS
PILOTED SIMULATIONS
CORRELATION
JAWS DATA
MATHEMATICAL MODEL DEVELOPMENT
COMPUTER SIMULATION DEVELOPMENT
EVALUATION

Figure 1. Microburst Modeling Studies.

- How are these requirements currently met?

    - Wind shear

        - Wind model derivations from accidents/incidents, both Boeing in-house and FAA/SRI.
          (Our concern with this form of wind model is that it is possible to derive a variety of winds from the same accident/incident which leads to differing airplane response characteristics.)
          (See Figure 2)

        - Boeing (in-house) hybrid and synthetic models (arbitrarily determined). (See Figure 3)

    - Turbulence

        - FAA/SRI (judged unrealistic, based on simulator evaluation).

        - Theoretical representations of the von Karman & Dryden spectra.

- What analyses of data sets are needed to meet present requirements?

  Analysis of the JAWS data is required to validate fluid dynamic models of a standard microburst (Figures 4 and 5):

    - There is an immediate need for data to support a standard three-dimensional microburst representation within the critical range of 500 feet to the ground, including:

        - Velocity distribution laterally and vertically in the downdraft portion of the microburst.

        - Velocity distribution laterally and vertically in the outflow region.

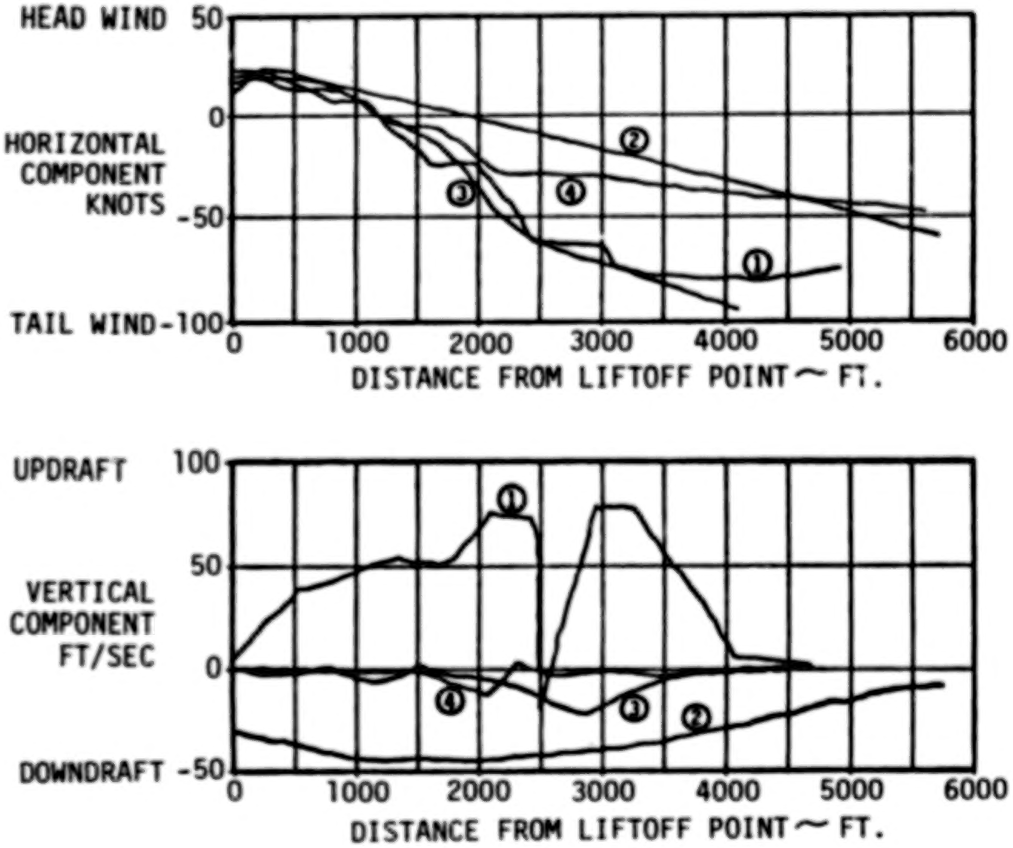
        - The relationship between average outflow velocities and average downflow velocities.

    - Also in the near-term, analysis of the JAWS data is required to establish statistical distributions of microbursts.

        - Establish statistical properties of horizontal wind shear rate, total horizontal wind change and maximum downdraft velocity near to the ground, including an error analysis (Figure 6).

        - Combine distribution diagrams if possible to produce a "total wind shear threat" diagram (Figure 7).

        - Establish whether JAWS data statistically fits the general pattern of global wind shear events, considering the major description characteristics.



FOUR
SEPARATE
WIND
ANALYSES
BASED ON
CONTINENTAL
FLIGHT #426
TAKEOFF
ACCIDENT
AT DENVER,
1975.

Figure 2. Currently Used Wind Shear Models--Accident/Incident Derivations.

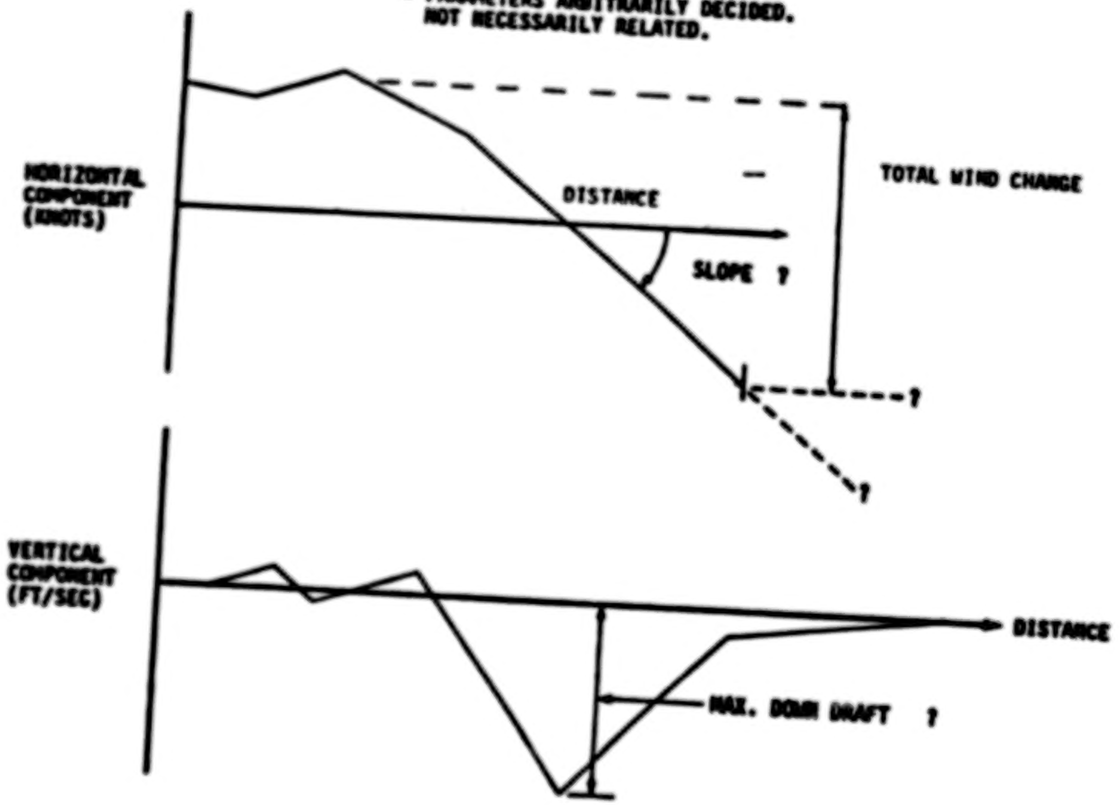

- PARAMETERS ARBITRARILY DECIDED.
NOT NECESSARILY RELATED.
HORIZONTAL COMPONENT (KNOTS)
DISTANCE
TOTAL WIND CHANGE
SLOPE ?
?
?
VERTICAL COMPONENT (FT/SEC)
DISTANCE
MAX. DOWN DRAFT ?

Figure 3. Currently Used Wind Shear Models--Boeing In-House Hybrid and Synthetic Models.

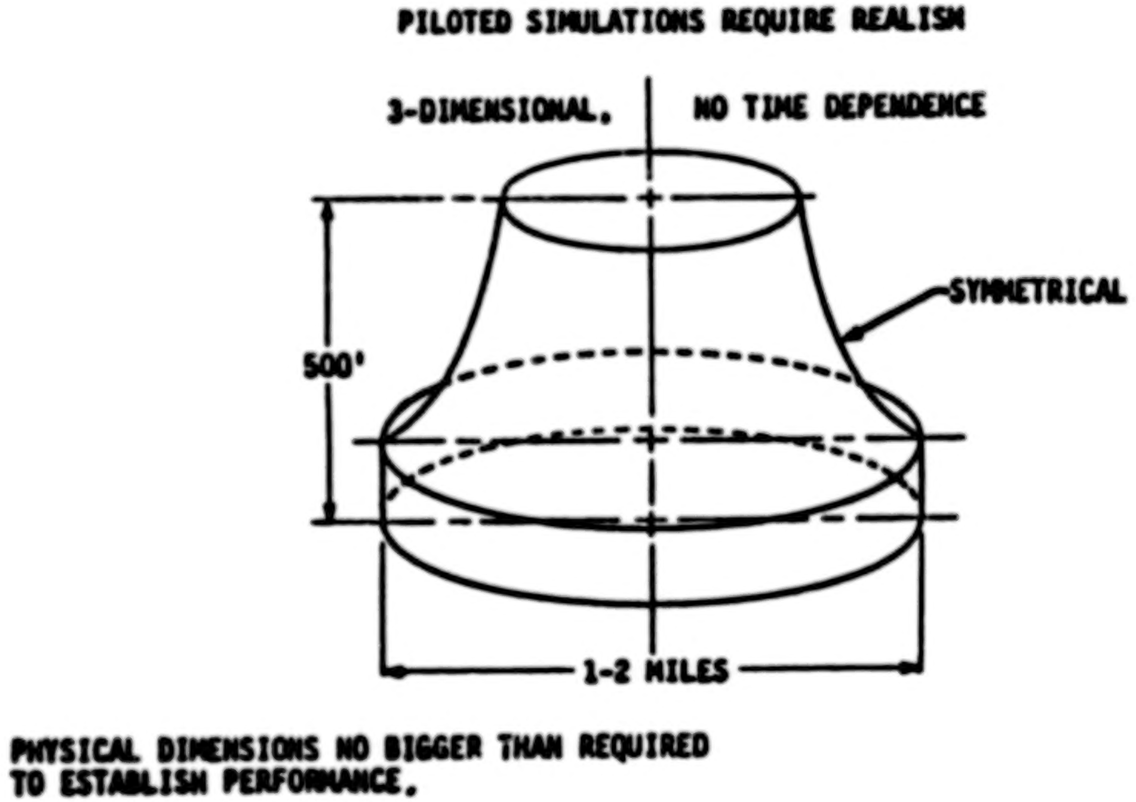
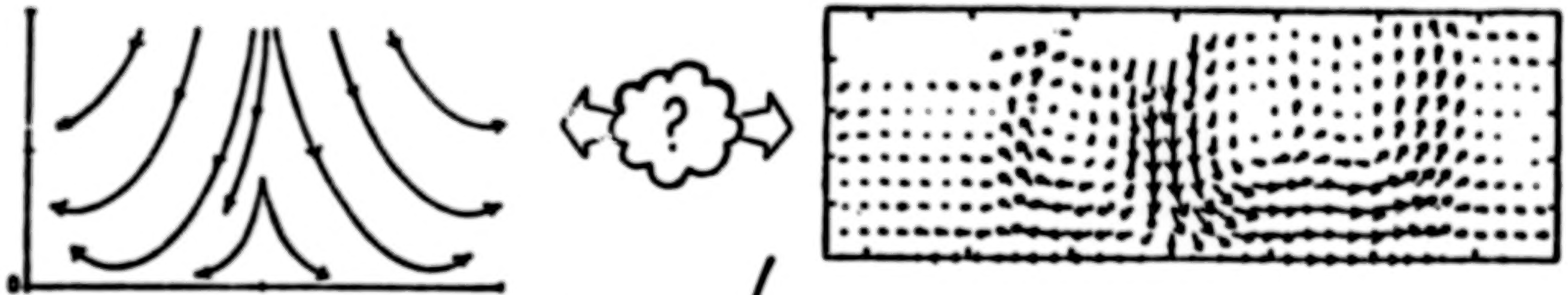
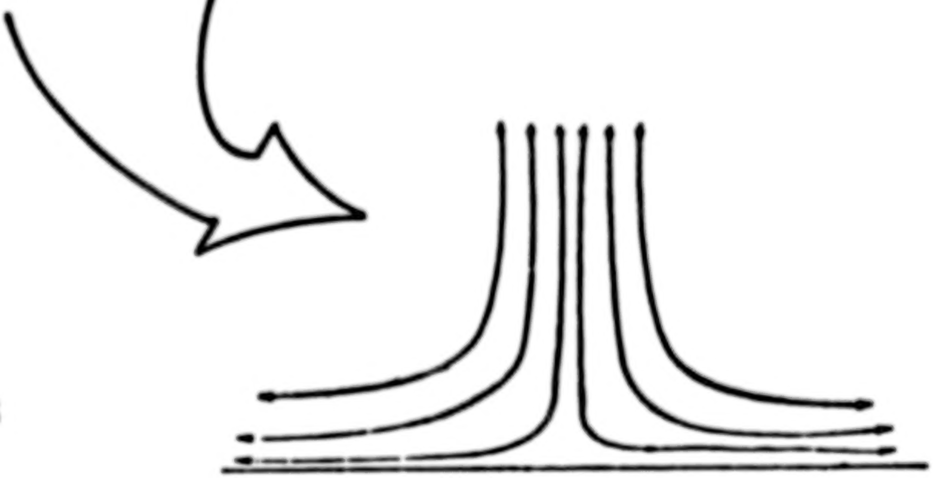

PILOTED SIMULATIONS REQUIRE REALISM
3-DIMENSIONAL, NO TIME DEPENDENCE
SYMMETRICAL
500'
1-2 MILES
PHYSICAL DIMENSIONS NO BIGGER THAN REQUIRED TO ESTABLISH PERFORMANCE.

Figure 4. Wind Model Selection Criteria.

- CLOSE THE LOOP BETWEEN THEORETICAL REPRESENTATIONS AND THE JAWS DATA

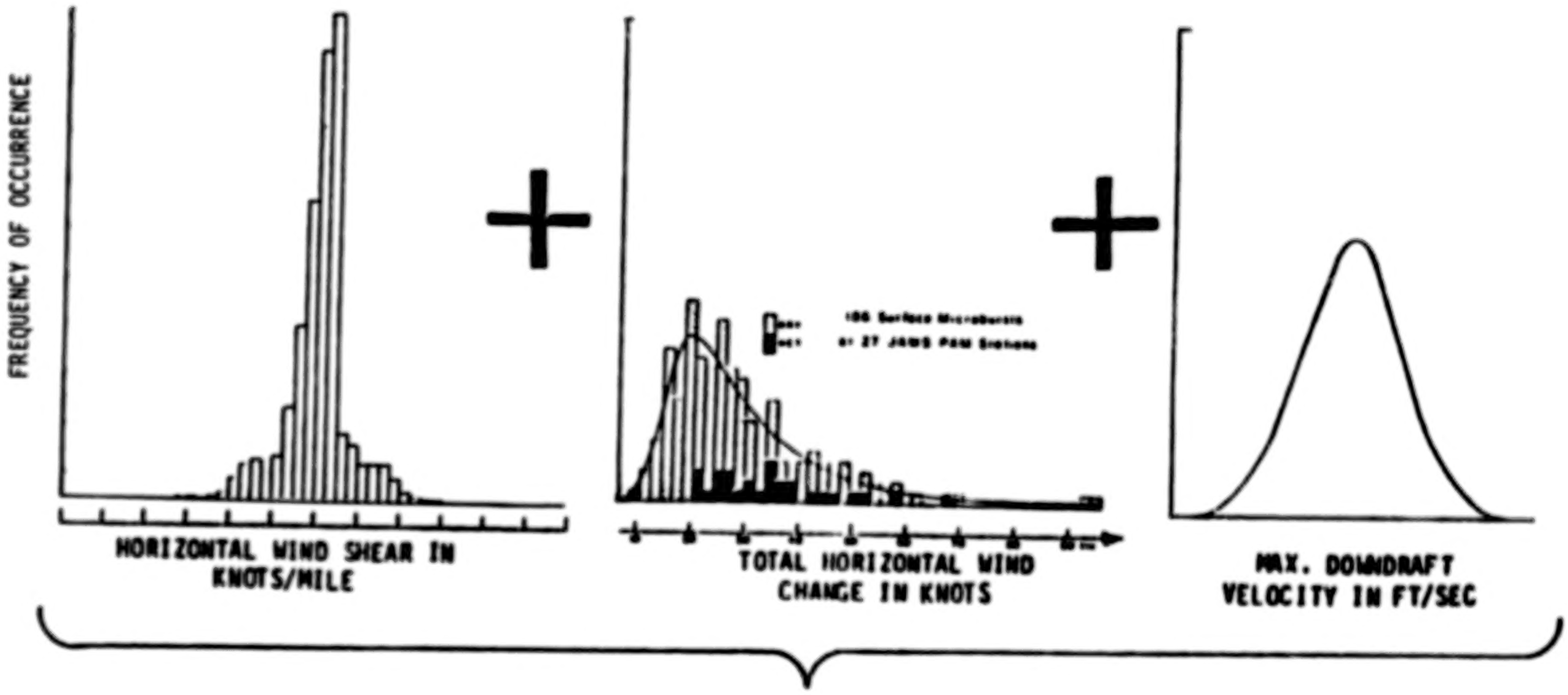




- OBTAIN A SET OF THEORETICAL MICROBURST MODELS:
  - REFLECTING MAJOR DESCRIPTIVE CHARACTERISTICS OF JAWS DATA
  - WITHIN STATISTICAL BOUNDS DETERMINED FOR DESIGN WORK

Figure 5. Required Analysis of JAWS Data--Theoretical Representation.

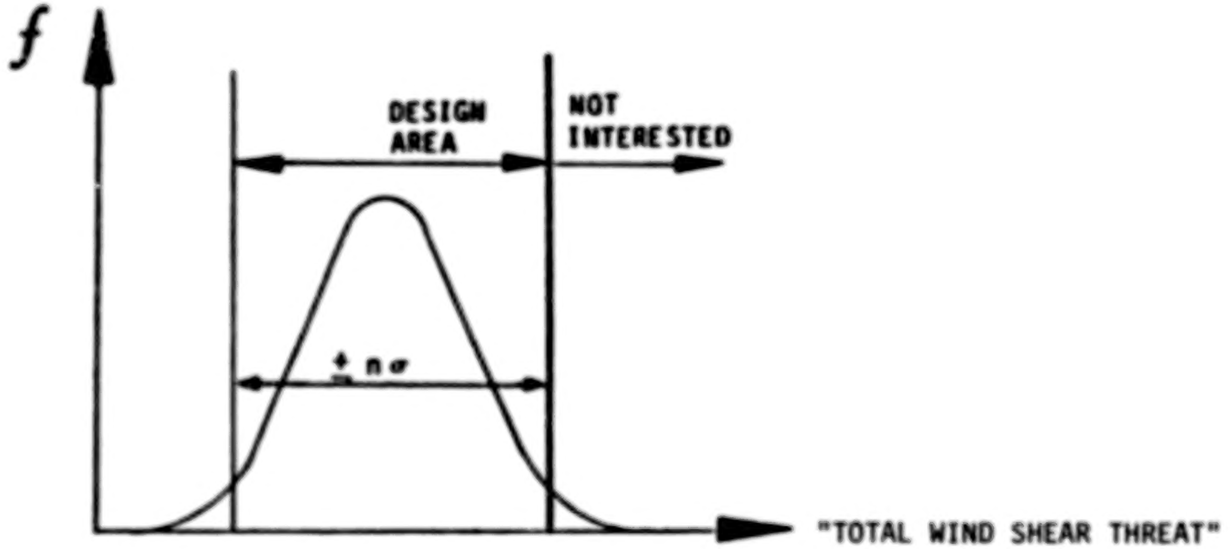
- ESTABLISH FREQUENCY DISTRIBUTION DIAGRAMS OF MAJOR WIND SHEAR CHARACTERISTICS



- COMBINE, IF POSSIBLE, TO FORM A "TOTAL WIND SHEAR THREAT" DIAGRAM

Figure 6. Required Analysis of JAWS Data to Establish Statistical Properties of a Microburst.

- MANUFACTURERS TO DECIDE HOW TO LIMIT MICROBURST CHARACTERISTICS ON "TOTAL WIND SHEAR THREAT" DIAGRAM


f
DESIGN AREA
NOT INTERESTED
$\pm n\sigma$
"TOTAL WIND SHEAR THREAT"

- CHECK CORRELATION OF JAWS STATISTICS STUDY WITH STATISTICS OF OTHER WIND SHEAR DATA BASES TO ASSURE DATA IS REPRESENTATIVE WORLDWIDE.

Figure 7. Required Analysis of JAWS Data--Statistical Analysis: To Produce a "Total Wind Shear Threat".

- What are the factors involved in the selection criteria for candidate mathematical representations?

  a. Should be representative of the real world in terms of major descriptive characteristic.

  b. Should be bounded for practical purposes to be no more than 1-2 miles wide and 500 feet high.

  c. Would have to decide where to cut off the frequency distribution diagram (number of standard deviations, $n\sigma$) for design work on the "total wind shear threat" diagram.

  d. Wind model would have to be 3-dimensional and symmetrical; i.e., stationary with respect to time.

IMPLEMENTATION OF WIND SHEAR AND TURBULENCE DATA SETS AND MODELS

- All wind and turbulence effects enter the simulation model through aerodynamic effects, primarily angle of attack and sideslip, and the related rate terms.

- The coefficients for the angle of attack and sideslip rate terms presently produce inconsistent results. This problem is under investigation.

- Rotational components of wind shear are not presently included. It is planned to include these components when a fluid dynamic downburst model is implemented. These effects need careful study as the airplane shows selective sensitivity to the wind gradient components, which may be combined to produce a rotation.

WHAT WIND SHEAR AND TURBULENCE DATA AND MODELS DO YOU ENVISION WILL BE REQUIRED TO MEET YOUR FUTURE PROGRAM OBJECTIVES?

- There is a longer term need to answer more general questions to provide a better understanding of the microburst phenomenon, including:

  - Considering the microburst events to be a superposition of a steady wind and a microburst, what was the range of values of the steady wind component?

  - What range of altitudes characterizes the starting point of the downdraft?

  - How does the size of the microburst vary as a function of time?

  - What was the range of downflow and outflow velocities?

  - Based on B-57B data, what spanwise gradients were measured in the vicinity of microburst extremities?

- The interrelationship between turbulence and wind shear.
- The pressure distribution within the microburst.
- Other characteristics of the microburst that may affect the aircraft system performance.

QUESTION:

In the interrelationships between turbulence and wind shear, will you also include the interrelationships of reflectivity in that data set?

RESPONSE:

Yes. We are very interested in what can be done with airborne radars, and we would like to understand what reflectivity information is available.

REFERENCES

1. Low-Altitude Wind Shear and Its Hazard to Aviation. National Academy Press, Washington, DC, 1983.
2. Usry, J.W.; and Dunham, R.E.: Low-altitude wind shear statistics derived from measured and FAA proposed standard wind profiles. AIAA-84-0114, 1984
3. Woodfield, A.A.; and Woods, J.F.: Worldwide experience of wind shear during 1981-1982. Flight Mechanics and System Design Lessons From Operational Experience, AGARD-CP-347, 1983.

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AUTOMATIC SYSTEMS AND THE LOW-LEVEL WIND HAZARD

Dwight R. Schaeffer
Avionics Division
Sperry Flight System

ABSTRACT

Automatic flight control systems provide means for significantly enhancing survivability in severe wind hazards. The technology required to produce the necessary control algorithms is available and has been made technically feasible by the advent of digital flight control systems and accurate, low-noise sensors, especially strap-down inertial sensors. The application of this technology and these meanshas not generally been enabled except for automatic landing systems, and even then the potential has not been fully exploited. To fully exploit the potential of automatic systems for enhancing safety in wind hazards requires providing incentives, creating demand, inspiring competition, education, and eliminating prejudicial disincentives to overcome the economic penalties associated with the extensive and risky development and certification of these systems. If these changes will come about at all, it will likely be through changes in the regulations provided by the certifying agencies.

INTRODUCTION

The task of improving aircraft safety for the low-level wind hazard takes two forms:

1) Detection and avoidance;
2) Enhanced survivability.

The approaches emphasized for survivability have been:

- Pilot training and procedures;
- Airframe/engine capability;
- Displays and annunciations.

Another approach that currently receives less emphasis than the others, but which offers greater potential, is the use of automatic systems, both coupled systems, which control aircraft motion unassisted, and director systems, to provide commands which the pilot controls.

Simulations of low-level shear hazards that have been associated with major incidents have confirmed the marginal ability or inability of pilots to cope with the hazard. Yet, the same simulations are used to demonstrate the high capability of automatic systems not only to survive the hazard, but to maintain precision tracking. Too often, major incidents occur after the pilot has turned off his automatic system, either by choice or by requirement.

Automatic systems have the ability to receive and quickly process large amounts of data simultaneously, and, thereby provide much quicker detection and reaction to a wind hazard than a pilot. The time to detect and react is frequently more important than the magnitude of the control applied. The longer the detection/reaction time, the greater the magnitude of the control required.

On the other hand, the pilot frequently has advantages of:

- Greater control authority and rate capability;
- Flexibility and adaptability;
- Less susceptibility to hazardous reaction to failures;
- Access to more controls, particularly secondary controls.

The advantages the pilot has over automatic systems are generally not inherent; the technology required to reduce or eliminate these advantages is available. Enabling the application of, or creating the demand for, this technology is the challenge.

In the following, the available technology and other potential means and needs for enhancing the capability of automatic systems to cope with wind hazards are discussed qualitatively.

CONTROL ALGORITHMS

At one time, the unavailability of quality sensors and computational capability for a reasonable amount of analog hardware restricted control algorithms to little more than a raw error signal operated on by a proportional gain. integral control and gain, and perhaps a rate damping term. A few gains dictated all aspects of automatic control; stability, tracking performance, activity in response to sensor noise and disturbances, and response to commands. Development of the control algorithms was more an exercise of seeking the best compromise. Sometimes filtering was added to reduce the effect of high-frequency activity from noise and disturbances, thereby permitting higher gains, but the tracking performance from the higher gains was largely offset by the adverse effect filtering had on stability and performance. Any increase in performance had an attendant increase in disconcerting activity and a tendency towards limit cycling due to rate saturation. The most important feature of the automatic mode, particularly speed control modes (by elevator or throttle) operating in a changing wind environment, may well have been the disconnect buttons or, at least, those buttons that revert to pitch and roll altitude command modes and allow the pilots to be the outer loop algorithms. Not only was there a hesitancy to seek higher levels of tracking performance for the variable wind environment (a fruitless exercise since the pilot would disengage the system due to the high level of attendant non-productive activity), there were overt attempts to degrade performance for the more severe wind environment so that the non-productive activity would remain within acceptable bounds (the "TURB" button).

The introduction of the digital computer has provided a tremendous computational capability. Combined with the new generation of high-accuracy, low-noise digital sensors, especially strap-down inertial sensors, a new architecture for control algorithms has been enabled.

- The former error signals can be split into the target and feedback components, which are processed separately before combining to form new error signals.

- The targets can be processed linearly and non-linearly to shape and control target acquisition without affecting stability and response to noise and disturbances.

- The feedback signals can be blended with inertial data to provide a signal having the static accuracy of the raw feedback signal and the low-noise, high-dynamic accuracy of the inertial signal without significant effects on stability and tracking performance. This blending can include the removal of sensor location effects resulting from coupling with angular motion.

- Comparison of air data and inertial data can be performed to derive wind components and their derivatives which can then be processed linearly and non-linearly before re-introduction into the feedback signal. This allows a high degree of independence between response to shear, response to turbulence, still air tracking performance, and stability.

- The derived wind components can be used for predictive control corrections that are applied as the wind disturbance occurs, but before feedback signal disturbances, thereby preventing the signal disturbances.

- The derived wind signals can be used predictively to remove the deterministic "noisy" responses of inertial signals to turbulence.

The result of applying these and other techniques is a much higher level of tracking performance for the previous level of unproductive activity. The feedback gains for attitude and path control functions can now be increased to the stability limits with virtually no increase in activity due to turbulence and no adverse effect on target capture performance.

For modes that control airplane motion relative to the air mass, principally airspeed modes, the trade-off between performance activity remains, though weaker and with much better performance for the same activity. This is principally due to the still imperfect inability to distinguish between the wind speed changes that will continue (shear?) and those that abruptly change (turbulence?).

The development of these modern control algorithms to maximize tracking performances in winds with acceptable activity and good maneuvering characteristics, required to gain the pilots trust and acceptance, does not come cheaply, quickly, nor without high technical risks. They, therefore, tend to be applied for terminal area modes only where required, specifically for Category III automatic landing, where the regulations on touchdown dispersions and airspeed control in winds are very stringent.

The availability of Category III automatic landing systems is limited principally to commercial transports. They are not used extensively for long-range aircraft due to the need for the pilot and co-pilot to perform a minimum number of manual landings each month to maintain their proficiency and to the limited number of landings available.

Category I and II automatic approach systems do not require tracking as tight nor do they require autothrottles. Hence, the survivability they provide in severe winds is not as good.

When coupled go-around modes are provided, they frequently do not provide closed-loop speed and path control, but only assure positive acceleration and vertical speed for a range of weights and thrust in still air. Go-around flight director modes may consist of nothing more than a fixed-pitch attitude command.

Coupled takeoff modes are not provided at all, even though an airplane fully equipped for a Category III-B automatic landing is also equipped to perform a "Category III-B automatic takeoff", if regulations existed to cover such a mode. One argument against such a mode is the lack of airports equipped with localizer deviation or the equivalent to enable steering down the runway for takeoffs. A similar argument was used against Category III-B automatic landings. Coincidently, when the latest commercial aircraft were being developed with Category III-B automatic landing capability as standard equipment, there was an explosion in the number of Category III-B certified airports in the U.S.

Like the go-around function, the automatic takeoff pitch control function is essentially a speed control task. By controling speed, thrust in excess of that required for level flight is converted to vertical speed. Complexity may be added to prevent selecting too low a speed (by estimating the equivalent of a minimum speed using angle of attack, inertial data, and configuration sensors) and to force a thrust deficiency to cause a speed reduction rather than a loss of altitude. Additional complexity is needed for the takeoff flight director to accommodate the pilot's rotation without over-shooting the attitude required for stabilized speed.

By employing airspeed and vertical speed blended with inertial data and inertial acceleration, speed control through pitch control can counteract the effects of variable winds. However, many takeoff flight directors provide nothing more than a fixed-pitch attitude command for all conditions. Even proposed advanced concepts plan to pre-compute a fixed-pitch attitude command based on pilot-entered weight, expected thrust, configuration, and ambient pressure and temperature. This attitude command would then result in the correct climb-out airspeed when controlled, but only in still air.

Takeoff autothrottles rapidly advance thrust to a selected setting, then disengage during the ground run at a predetermined airspeed so as to protect against a failure that could cause a thrust reduction. Whenever excess field length exists for the available thrust, the choice is invariably made to reduce the thrust setting so as to save engine life rather than to use all the thrust to accelerate to a higher rotation and climb-out in order to increase climb capability and speed margins. With the autothrottle inhibited from engagement, it does not attempt to detect an energy deficiency, as may occur in variable winds, and then advance thrust to the maximum available.

CONTROL AUTHORITY AND FAILURE PROTECTION

The classic method of preventing a failure that could cause an automatic system to command so much control surface so as to cause structural failure or a dangerous maneuver is to limit the control surface that can be commanded to a "safe" maneuver level. This limiting is achieved by servo displacement limits or by limiting the force or torque the servo can produce against the force or torque from the surface hinge moments or the control feel unit. The problem with this technique is that it also limits the control authority available to a non-failed system to counteract the effects of severe disturbances.

The "fail-safe" maneuver becomes excessive for operation near the ground, yet the control authority required at low speeds, even in still air, may easily exceed the fail-safe limits. Hence, for a Category III automatic landing system, two or more systems, each with their own servos, are used with their limited authorities summed to increase control authority when the multiple systems work together. When one system fails, the good systems counteract the failed system's command.

The control authority available from simultaneous multiple automatic systems is seldom provided for other than automatic landing systems and even then may not match the capability of the pilot. An aircraft equipped with a Category III automatic landing system is equipped to provide multiple system operation for all flight phases; therefore, it enhances survivability in severe winds. The additional expense is associated with much more testing and is substantial.

Most aircraft, especially smaller aircraft, are not equipped for Category III automatic landings because of the high cost, weight, and power consumption of the redundant equipment.

Digital computers have enabled an alternative approach--the self-monitored system. The processing capability is used to analytically detect failures in sensors, servos, and within the processor itself. This approach can eliminate the need for multiple servos for fail passivity and authority limiting fail safety, but the development and testing of the monitors required is very extensive and expensive.

The monitoring approach can also be used to raise low rate limits applied to protect against oscillatory failure and flutter coupling. These low-rate limits not only prevent the control command from keeping up with the disturbance, but, when saturated, can also cause a biased target or unstable limit cycling.

Pitch control authority can be further enhanced by quickening the trim response to trim command and increasing trim rate. Trim motion is typically delayed in response to a trim command all the time in order to prevent the trim from increasing the maneuver response to a hardover failure before a pilot reacts to the fault. Failure monitoring can eliminate the requirement for the delay. The trim rate available to the automatic system is typically half or less than that available to the pilot, although there is no failure requirement to force this disparity.

The subject of authority also includes lift. Some automatic functions are designed to prevent the attainment of additional lift near stall that might otherwise be used to prevent loss of altitude in a severe wind hazard. Systems that are allowed to operate near stall must be disconnected upon the onset of stall in order to prevent the natural automatic control reaction that is opposite to that required for stall recovery. To enable the additional lift near stall to be available, a very high accuracy and performance control algorithm is required to prevent stall, yet not interfere with very near-stall lift attainment.

INCENTIVE/DISINCENTIVE

The major challenge of enhancing safety for wind hazard, no matter what the means, is enabling the application of technology. This is a matter of creating incentives, eliminating disincentives, or creating disincentives for not enhancing safety. Sources of these incentive/disincentives are interrelated and include:

- Regulations
- Competition
- Economics
- Education

For the most part, regulations address disincentive. They don't say how a characteristic must be achieved, although FAA advisory circulars tend to promote methodologies by describing acceptable approaches, but describe what minimum characteristics an aircraft must have before it can be sold and what requirements optional functions must have. Regulations principally address safety and truth of advertising (satisfaction of intended function).

There's little doubt that the regulations governing automatic landing systems are responsible for the relatively high levels of performance of these systems in variable winds, although the homogeneous boundary-layer wind and turbulence models suggested may be lacking in accuracy and severity. Perhaps more important than updating these models is the application of similar treatment to other terminal area automatic modes.

Except for the automatic landing system, there is no quantitative minimum requirement for wind hazard survivability. Wind and turbulence models for automatic landing system simulation are analytic and parameterized. Minimum requirements are specified in terms of tower wind component levels and variation of horizontal wind with altitude. Minimum requirements are low and aircraft manufacturers usually seek certification to higher wind levels to enable automatic landings for more conditions. The test, however, is against the objective certification level. Seldom are efforts made to determine the maximum level of wind hazard the system is capable of surviving. There are no requirements for simulation demonstration of survivability in the severe non-homogeneous wind disturbances such as microbursts and storm fronts, although aircraft manufacturers do test these systems in simulations of these severe hazards.

An obvious question arises: Should regulations require minimum wind hazard flight control survivability, at least for terminal area operation? Requirements do exist for structural survivability. Such requirements would involve specification of the wind hazard model and a means for measuring success. The requirement should not specifically address automatic systems, rather automatic systems would be one of several means for showing compliance. Capability in excess of the minimum requirements could be rated; then this rating, similar to the automobile's estimated miles per gallon, could be a means for spurring competition and increasing awareness.

Part of the incentive for providing automatic systems is lost because regulations have two standards for manually and automatically controlled flight, and because they do not give credit for the superior performance of the automatic system. For example, although an automatic landing system may clearly demonstrate greater survivability in a wind shear hazard than manual flying, that same automatic system will likely be certified to conduct automatic landings in wind conditions less severe than is the pilot. This is because manual landing capability and performance are not based on the same strict standards that apply to automatic landing systems. Additionally, though approach airspeeds are not increased for increased wind severity for automatic landing systems as they normally are for manual flying, and though an automatic system may demonstrate much less likelihood of touching down long than a pilot, the field length requirements are the same for both. Field length requirements don't even reflect the tendency for manual landings to touch down at higher speeds for more severe winds.

New automatic systems tend to be introduced only at the same time as new aircraft with a short development cycle, although additional features may be added to an existing aircraft. This is the worst possible time to aggressively seek the large potential benefits that entail technical and program risks. There is great pressure to reduce goals and assure that a system with lesser capability works well; the superior characteristics of an automatic system will not likely sell airplanes, but the inferior characteristics might prevent airplanes from being sold. A high-performance automatic system requires good detail models of aerodynamics, the control system, and sensors. New program pressures and the concurrent development of the airplane configuration, control system, and sensors prohibit that detailed modeling.

The best time to develop or, at least, evolve a high-performance automatic system is after an airplane is in production. If the evolution takes place, there is less need to make large technological advances during the development of the next new airplane.

The difficulty is convincing the customer he needs a new automatic system when his present one is performing adequately, particularly if the purpose is to enhance safety for what is perceived as an extremely remote event.

There is also a major role for education to play in eliminating disincentive. The pilot must be convinced that the severe wind hazard he could not cope with on the simulator is real, not an artificial contrivance, even though he never has and likely never will experience a similar hazard in flight. The pilots and airline passengers must be educated that attitude changes and engine modulations are indicative of tight control necessary to insure safety in the event that the change in wind experienced persists or subsequently changes more violently.

QUESTION:

Do you think that a realistic goal would be certification requirements for the design of the airplane and systems that are compatible with the airplane's performance?

RESPONSE:

I think the certification requirements of the automatic system are quite precise, and that is probably more of a standard, although it's a very exhaustive and expensive certification to go through. I guess what I was implying is that they talk about the airplane's capability, but when they measure the airplane's capability, it is actually an airplane/pilot capability. If you force the airplane pilot to go through the same kind of standards, then you probably would see a disparity and would come up with different conclusions as to what the capabilities were.

QUESTION:

Could the logic of the system be designed such that it will extract the maximum performance of the airplane through a given encounter?

RESPONSE:

Unfortunately, there are two sides to the story. You always pay for something that you get, particularly in the performance area, and particularly in speed-control modes, which is your principal means for counteracting. That is, under benign conditions, you may have more activity. Generally, the higher performance you get, the higher the activity, and you will be pressured to make sure that you are providing very good characteristics for the still-air environment, even if it means sacrificing for the more severe. I say part of that is going to come out of aducation, and maybe part of that comes out of our regulations. It's going to take somewhat of a change of attitude.

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SIMULATOR MANUFACTURERS' REQUIREMENTS

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Introduction

As simulator manufacturers, we must continue to provide to our customers the latest wind shear models available for pilot training. The release of the JAWS data package enabled us to provide a much more realistic wind shear package to our customers rather than just the standard six SRI wind shear profiles currently in use. In this brief presentation, the steps taken in implementing the JAWS data into our FAA 727 simulator are highlighted.

Implementation of the JAWS Data Package

The entire data set was loaded into one of our development computers to conduct some preliminary testing. We decided to select a subset of the JAWS data for the simulator since we did not believe that it was necessary to have the whole data set available on the simulator.

We were provided with time histories of a standard three-engine missed approach flown on our United Airlines 727 simulator (see Figures 1 and 2), which the FAA requested us to use as a baseline for evaluating the severity of the microburst data. Choosing the origin of the microburst as shown in Figure 3 and placing this origin at the touchdown point, several missed approaches were tried along the suggested flight paths. The effects of the microburst on altitude, airspeed and pitch angle are shown in Figure 4. Since there was no corrective action taken by the pilot, and there was no provision for altering the initiation of the go-around procedure, these results clearly do not imply that ground contact is inevitable in this case, but only that this microburst is severe enough to indicate that standard procedures are not sufficient to survive this encounter.

After demonstrating several of these automated missed approaches to the FAA, it was decided to implement the entire region shown in Figure 3, which measures 6.6 km^2, into the simulator. We feel that we are providing the FAA with a reasonably large region of the JAWS data to evaluate which includes severe, moderate, and weak wind shear flight paths.

Instructor Station Control of the JAWS Data

In order to provide flexibility to the instructor, the data has been implemented in such a way that the origin of the microburst (whose default position is centered at the touchdown point and orientation along the runway heading) may be translated relative to the touchdown point, and the orientation of the data block may be rotated, facilitating the task of evaluating the various flight paths (see Figure 5). In addition, although physically unrealistic, the FAA requested that the base altitude of the microburst be adjustable if necessary so as to inhibit ground contact during evaluation and training.

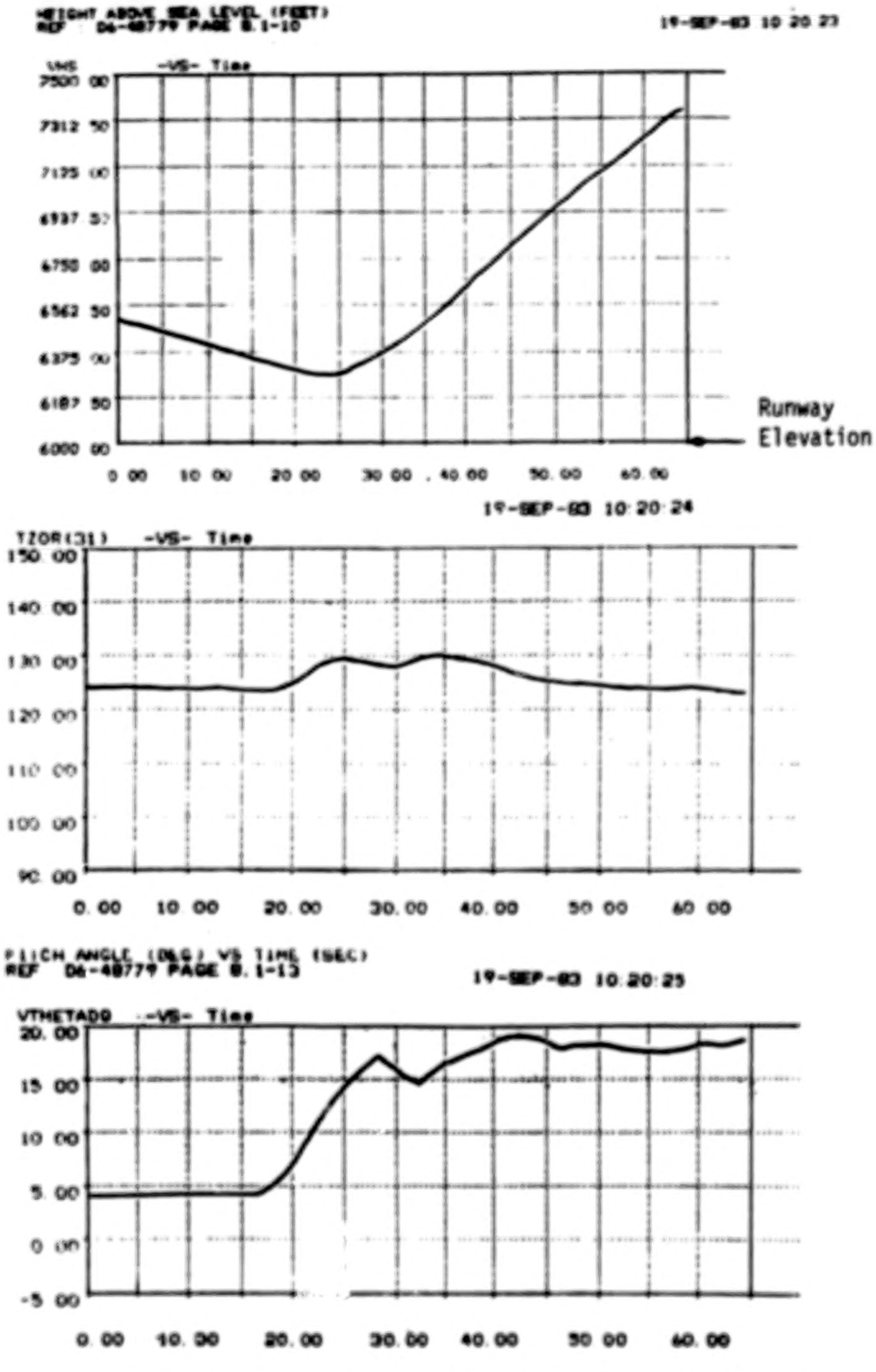

Figure 1. Altitude, airspeed, and pitch angle time histories of a standard three-engine missed approach.

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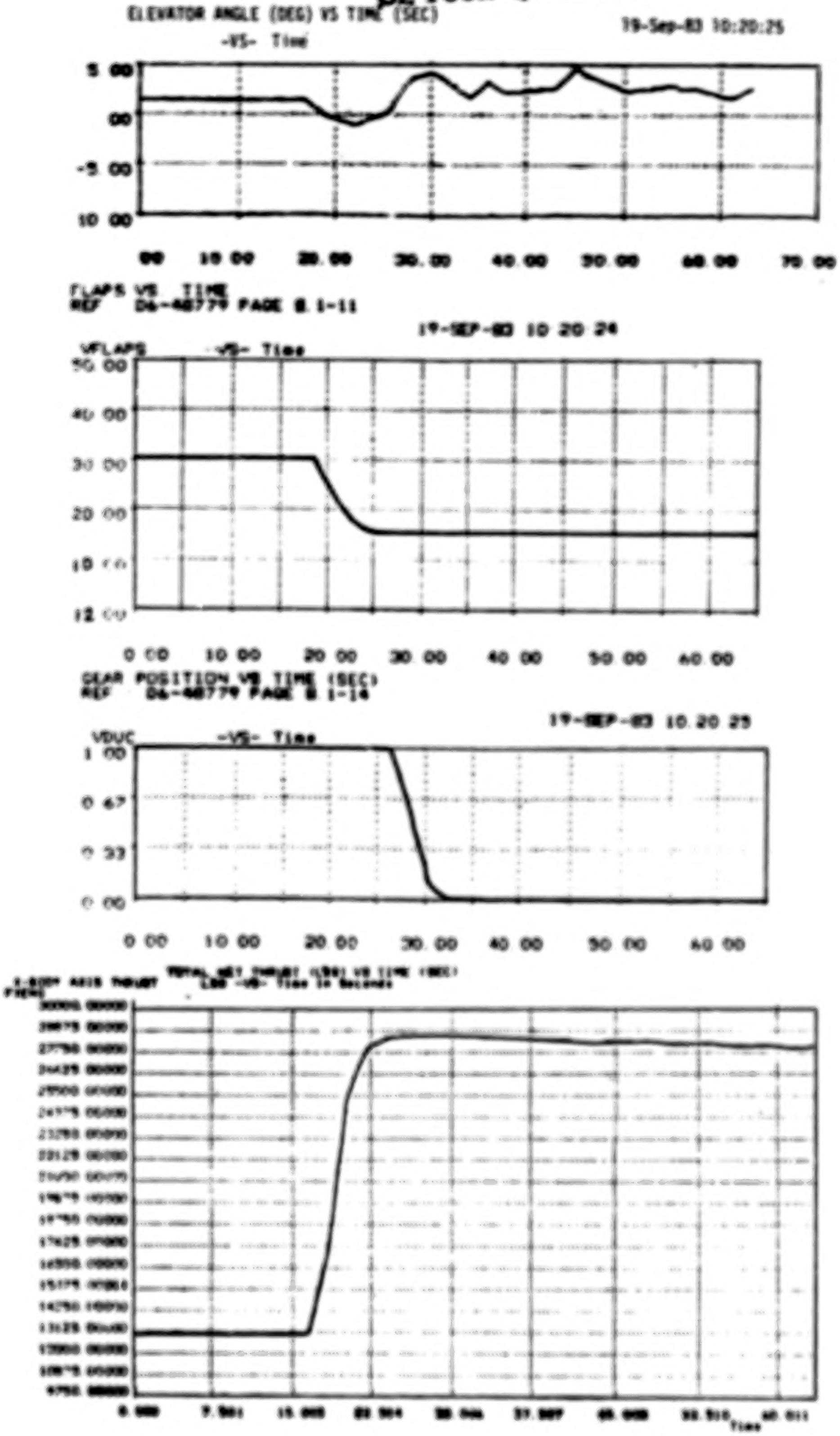

Figure 2. Elevator, flap, gear, and thrust time histories of a standard three-engine missed approach.

FLIGHT PATHS OVERLAID ON HORIZONTAL WIND SPEED VECTORS

WIND FIELD AT GROUND LEVELS
August 5, 1982 Data Set

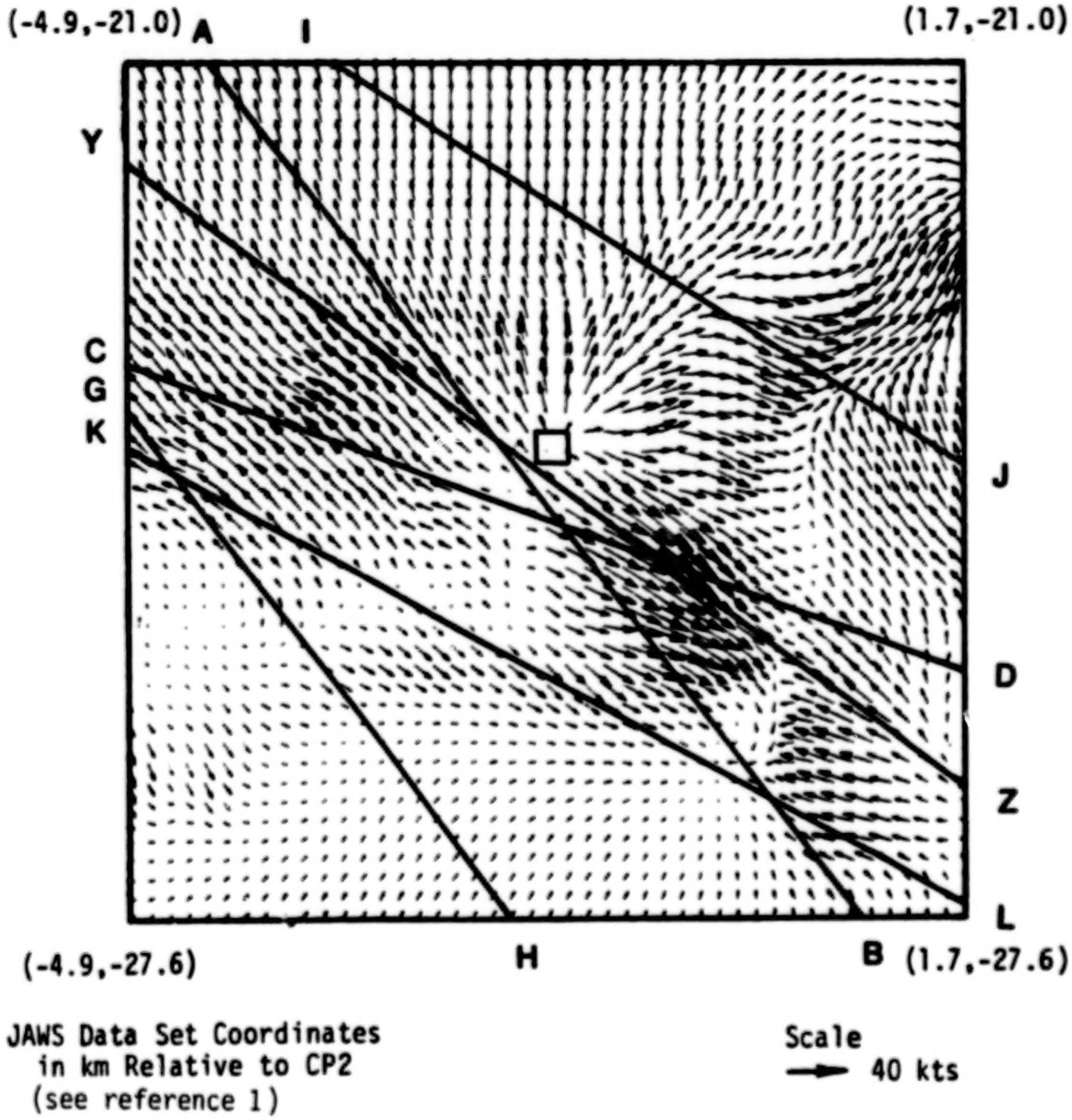

Figure 3. Region of JAWS data used in the simulator.

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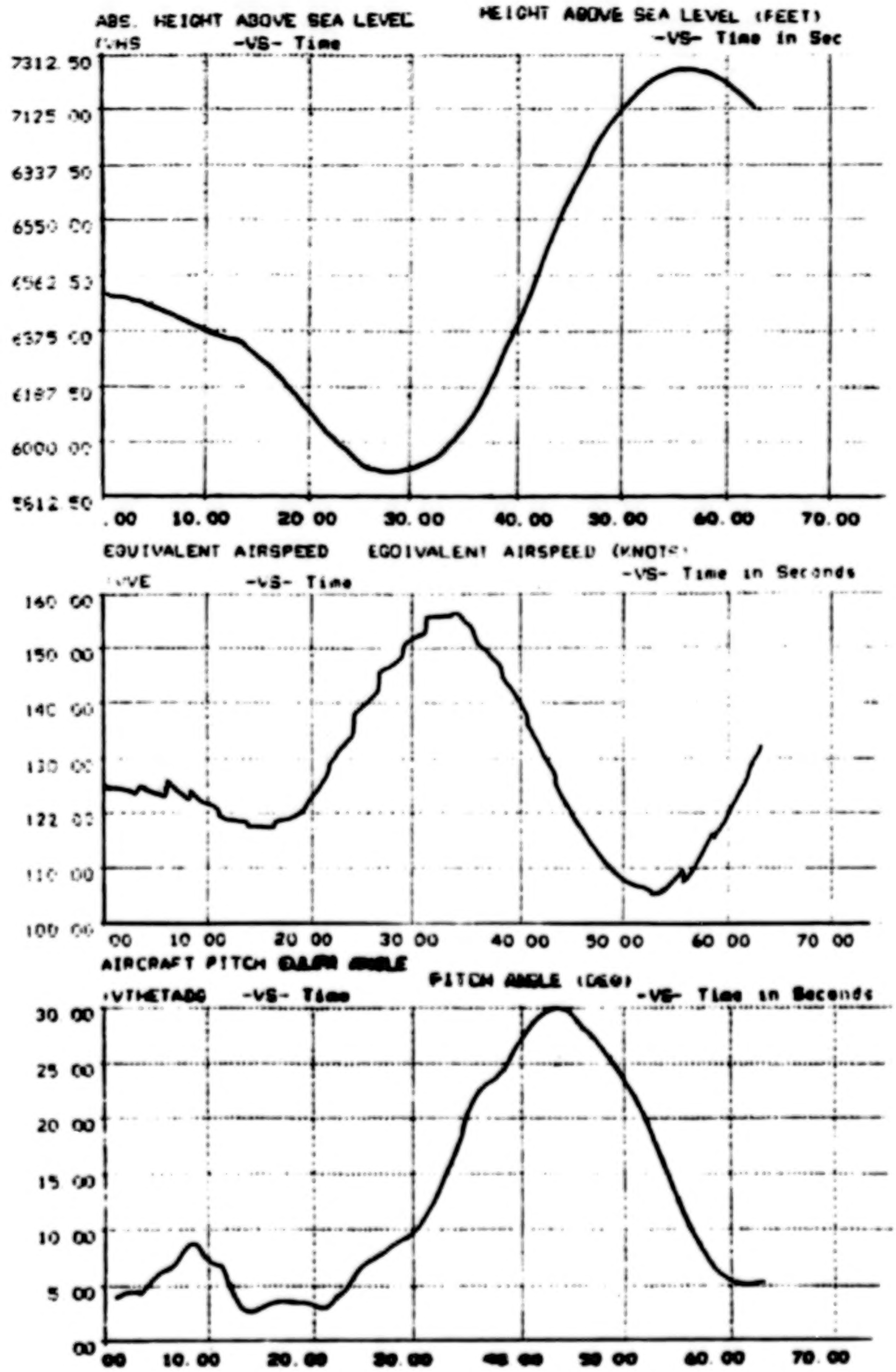
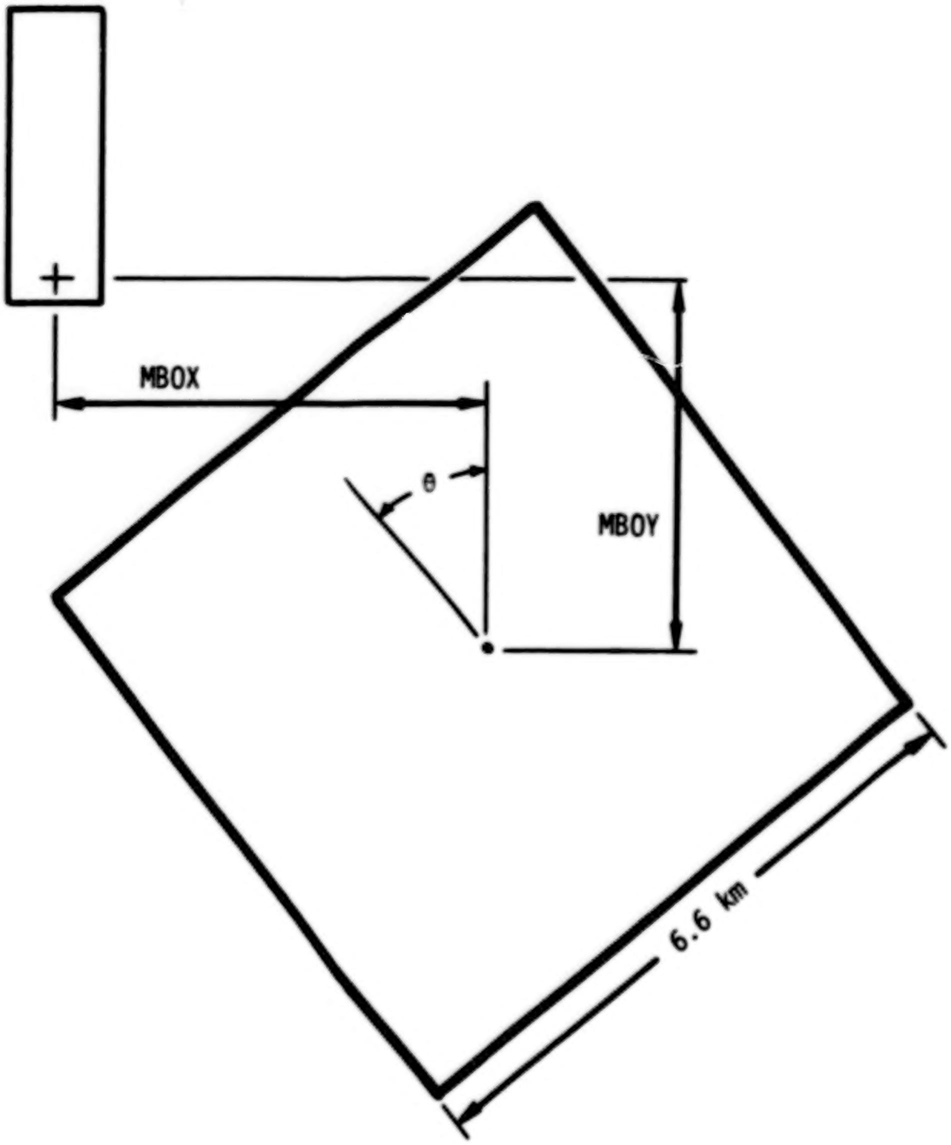


Figure 4. Altitude, airspeed, and pitch angle time histories of a standard three-engine missed approach flown through the center of the microburst.



MBOX - Microburst origin lateral offset

MBOY - Microburst origin longitudinal offset

θ - Angle of rotation with respect to runway heading

Figure 5. Parameters used to modify microburst location and orientation.

To further the evaluation of pilot performance during approach and landing, it will also be possible to superimpose a plot of the microburst region on the ILS graph as shown in Figure 6. The instructor may then monitor the entry into the microburst, the glidepath and localizer deviation and airspeed while flying through the microburst and on through to touchdown or go-around. A hard copy may then be obtained for further study.

Summary

Although we have no feedback from pilots as of yet, we feel that the JAWS data set will provide far more realistic and difficult wind shear profile encounters than what is presently used and should, therefore, provide better training value. From a manufacturers point of view, the major questions to be answered are:

1) Would an analytical model of a microburst which is under our control be more useful in pilot training than the JAWS data?

2) Are much simpler models, which would still require similar flight path control measures, sufficient for training purposes?

REFERENCE

1. JAWS Project Operations Summary 1982. National Center for Atmospheric Research, Boulder, CO, 1983.

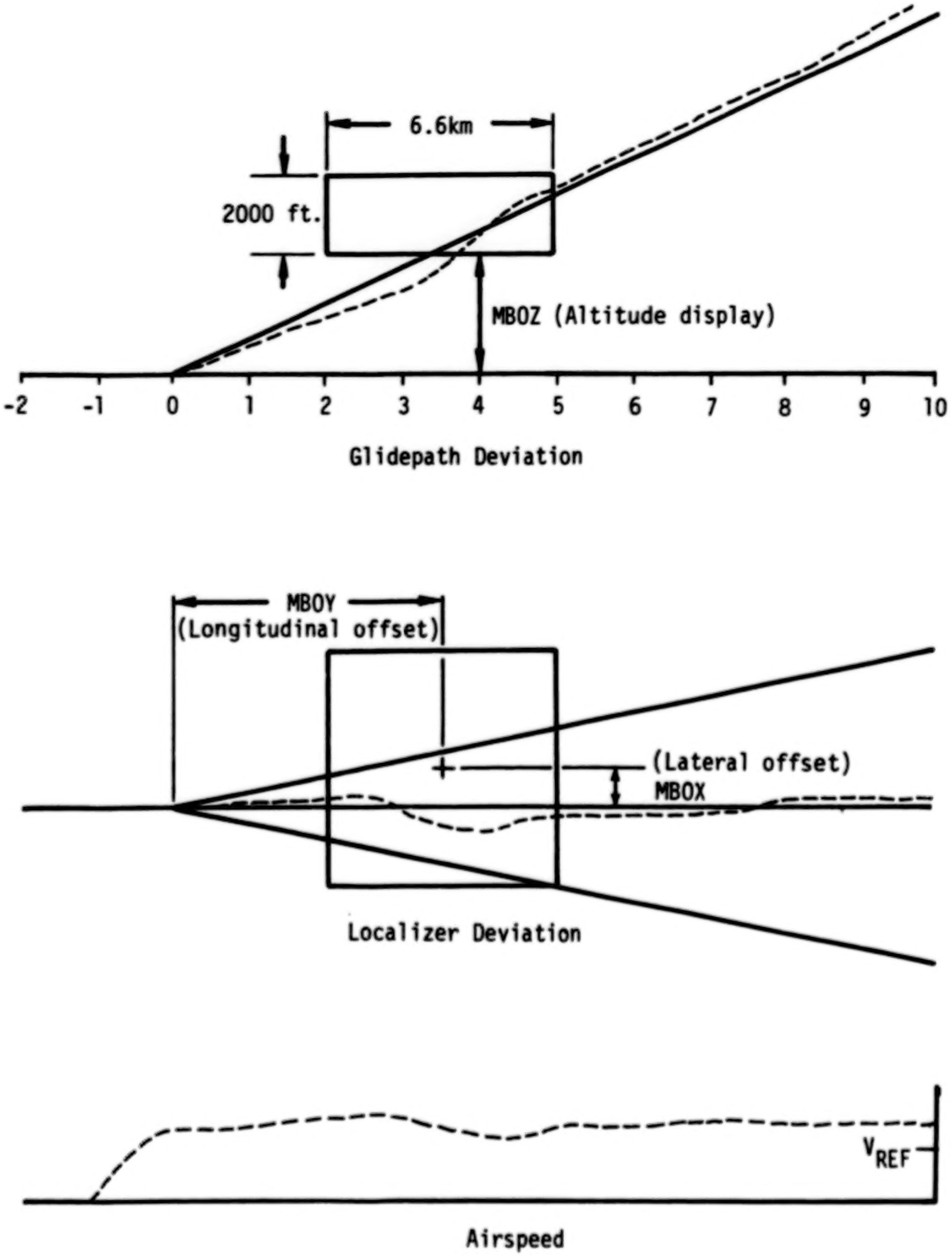

6.6km
2000 ft.
MBOZ (Altitude display)
-2
-1
0
1
2
3
4
5
6
7
8
9
10
Glidepath Deviation
MBOY
(Longitudinal offset)
(Lateral offset)
MBOX
Localizer Deviation
V_{REF}
Airspeed

Figure 6. Example of the ILS approach plot with the microburst region displayed.

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MILITARY SPECIFICATIONS

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INTRODUCTION

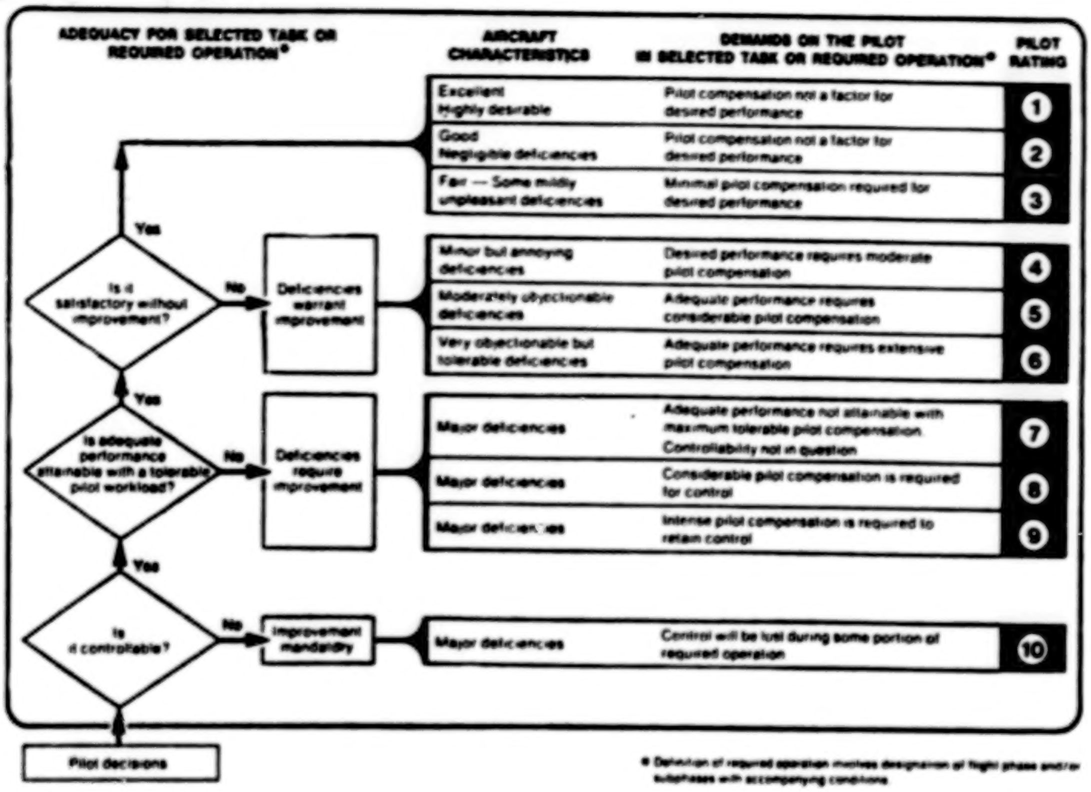
The current situation relative to the military specification is that there is not one specific model of turbulence which people are using. Particular disagreement exists on how turbulence levels will vary with qualitative. It does not tie you down to specifics. When it comes to flying quality specifications, many people feel that we should stay with the definitions of the Cooper-Harper rating scale, as shown in Figure 1, but allow the levels to shift depending on the level of turbulence.

RAE Bedford and British Airways have recorded thousands of landings, examined them, studied them, and tried to discover instances of encountering wind shear, and how many landings get close to the edge. Apparently, the British flight recording information is better than ours. It contains more information, such as the pilot's action; i.e., where the throttle is, where the wheel is, etc. If wind shear is encountered and the pilot goes to full thrust without the flight recorder being aware of this, the derived wind shear, or the reconstruction of the accident after the fact, may not be correct. Accident investigations at this time seem to look at where the throttle ended up and use this to reconstruct last few seconds of flight. In my opinion, this is not a good enough way to obtain a description of the encountered wind shear. You may come out with an entirely wrong answer.

There is a ride quality specification in the MIL-SPEC (reference 1) having to do with flight control systems design that is related to a turbulence model. The structures people also have specifications which relate to turbulence and the problems that they encounter. There is no lack of specifications in the military; it is simply that perple are using different models.

Reference 2 specifies isotropic turbulence models which are either the von Karman or Dryden as noted in Figure 2. Turbulence longitudinal scales twice the lateral scales are recommended. Equations that define the spectra are also provided in this document.

MIL-F8785C (reference 1) is the current version of the flying quality specification. It has a turbulence model, and it has the turbulence intensities, σ's, varying with altitude in the way shown in Figures 3 and 4. The scales vary with altitude. Mil-standard, which is a new proposed version of the MIL-8785, has the characterization also shown in Figure 3. We, at Calspan, have a third. You can see right away that in all models the scale L_w is proportional to altitude, so it goes to zero and zero altitude. The only difference in L_w between models is that Calspan uses a factor of two, so its scale is half the other model's value. When you plot the model parameters, you see that there is disagreement on how they vary. The mil-standard draft for σ_w is in the middle of Figure 4 and Calspan's suggestion is on the bottom. We are also working more now with helicopters and a helicopter specification is being developed. Figure 5 shows the probability that sigma exceeds a certain value given that you have encountered turbulence.


ADEQUACY FOR SELECTED TASK OR REQUIRED OPERATION*
AIRCRAFT CHARACTERISTICS
DEMANDS ON THE PILOT IN SELECTED TASK OR REQUIRED OPERATION*
PILOT RATING
Excellent Highly desirable
Pilot compensation not a factor for desired performance
1
Good Negligible deficiencies
Pilot compensation not a factor for desired performance
2
Fair — Some mildly unpleasant deficiencies
Minimal pilot compensation required for desired performance
3
Yes
Is it satisfactory without improvement?
No
Deficiencies warrant improvement
Minor but annoying deficiencies
Desired performance requires moderate pilot compensation
4
Moderately objectionable deficiencies
Adequate performance requires considerable pilot compensation
5
Very objectionable but tolerable deficiencies
Adequate performance requires extensive pilot compensation
6
Yes
Is adequate performance attainable with a tolerable pilot workload?
No
Deficiencies require improvement
Major deficiencies
Adequate performance not attainable with maximum tolerable pilot compensation. Controllability not in question
7
Major deficiencies
Considerable pilot compensation is required for control
8
Major deficiencies
Intense pilot compensation is required to retain control
9
Yes
Is it controllable?
No
Improvement mandatory
Major deficiencies
Control will be lost during some portion of required operation
10
Pilot decisions

* Definition of required operation involves designation of flight phase and/or subphases with accompanying conditions

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LEVEL 1 $PR \leq 3.5$

LEVEL 2 $3.5 < PR \leq 6.5$

LEVEL 3 $6.5 < PR \leq 9$

Figure 1. Cooper-Harper Handling Qualities Rating Scale. (from reference 3).

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VON KARMAN

DRYDEN

AFFDL-TR-72-41 (reference 2)

ISOTROPIC TURBULENCE
LONGITUDINAL SCALES EQUAL TWICE LATERAL SCALES

$$L_u = 2\,L_v = 2\,L_w$$

DEFINITIONS REFLECTED IN SPECTRA EQUATIONS

Figure 2. Continuous Turbulence Models.

Figure 6 shows data from a B-66 program which is a plot of the frequency of encounter based on the RMS value. The RMS values are typically computed from a 60-second record. Real turbulence is not stationary. The specification deals entirely with clear-air turbulence. It is not associated with thunderstorms or the large-scale phenomena being discussed here. This is a whole new area to address. If you look at a 60-second record of wind shear with conventional statistics, the RMS will be disproportunately large.

Figure 7 shows differences between the models. We have different definitions for light, moderate and severe. For instance, the British classify an RMS of 10 as heavy turbulence; Calspan classifies this value as the most severe that you would encounter, as far as the flying quality specification is concerened. The definition of light turbulence differs as well.

Figure 8 is an example of wind shear concepts prior to JAWS, different types of boundary layer profiles. None of these examples resembles the kind of wind shear being discussed here.

Figure 9 illustrates the other part of the design problem, which is a discrete wind disturbance. In a helicopter, for instance, if you are landing behind a treeline, you experience a decrease in wind and then get a jet effect near the ground below the level of the tree branches. I have landed at little airports in light airplanes where you get a very pronounced wind effect from trees which is very predictable. The wind disappears, and you just have to be ready for it.

For those of you who are not well-versed in the MIL-SPEC rating scale for flying qualities, Figure 1 shows a 10-point scale. Proper use of this involves a pilot asking himself questions and answering his own questions. This helps the pilot orient his thinking towards rating the handling qualities of the airplane for a specific task. The first question is whether the airplane is controllable. If it is not, the pilot is forced to give it a rating of 10. Another question is whether adequate performance is attainable with a tolerable pilot workload. All these questions are subjective. The pilot has to make a judgment about what is tolerable.

Table I gives the mil-standard suggested specifications. In extreme turbulence, it allows you to say that you still have a level-one airplane even though the flying qualities are such that control can be maintained only long enough to fly out of the disturbance. That's a pretty poor situation. In severe turbulence, a pilot rating of 7-1/2 can be called level one. At Calspan, we don't agree with that. We would like to see those definitions of levels stay the same and have a different level permitted when you get into heavy turbulence. For example, if you take a level-one airplane and fly into an extreme situation, you might have a level-three pilot workload at that point; that's okay as long as it's flyable and you can get out of it. That's the alternate way which we are proposing to view the effect of turbulence. For level one, the definition in turbulence would be that flying qualities are clearly adequate for the mission flight phase, as shown in Table II. You can accomplish the mission here in the military sense versus not accomplishing the mission, giving up, and coming home. You require this capability for light turbulence. In moderate turbulence, we are saying the capability is not required, and likewise for severe. At level two, you have flying qualities adequate to accomplish the mission flight phase, but some increase in workload or degradation of the mission in effectiveness both exist. In moderate

MIL-F-8785C (reference 1)

$$\sigma_w = 0.1\,U_{20}$$

$$\sigma_u = \sigma_v = \frac{\sigma_w}{(0.177 + .000823h)^{0.4}} \quad \text{BELOW 1000 FT}$$

$$L_u = L_v = \frac{h}{(0.177 + .000823h)^{1.2}} \quad 10 < h < 1000 \text{ FT}$$

$$L_w = h$$

MIL-STD (reference 4)

$$\sigma_u = 5 \text{ FT/SEC} \sim \text{MODERATE}$$

$$\sigma_w = .117\,h^{1/3}\,\sigma_u \quad 10 < h < 1750 \text{ FT}$$

$$\frac{\sigma_u^2}{L_u} = \frac{\sigma_v^2}{2L_v} \quad \text{THUS} \quad \sigma_v = \sqrt{2}\,\sigma_u$$

$$L_u = L_v = 145\,h^{1/3} \quad 10 < h < 1750 \text{ FT}$$

$$L_w = h$$

CALSPAN (reference 2)

$$\sigma_u = 6 \text{ FT/SEC} \quad \text{OPERATIONAL}$$

$$\sigma_w = .083\,h^{1/3}\,\sigma_u \quad h < 1750 \text{ FT}$$

$$\sigma_v = \sigma_u$$

$$L_u = 2L_v = 145\,h^{1/3} \quad h < 1750 \text{ FT}$$

$$2L_w = h$$

Figure 3. Dryden Model Scales and RMS Intensities.

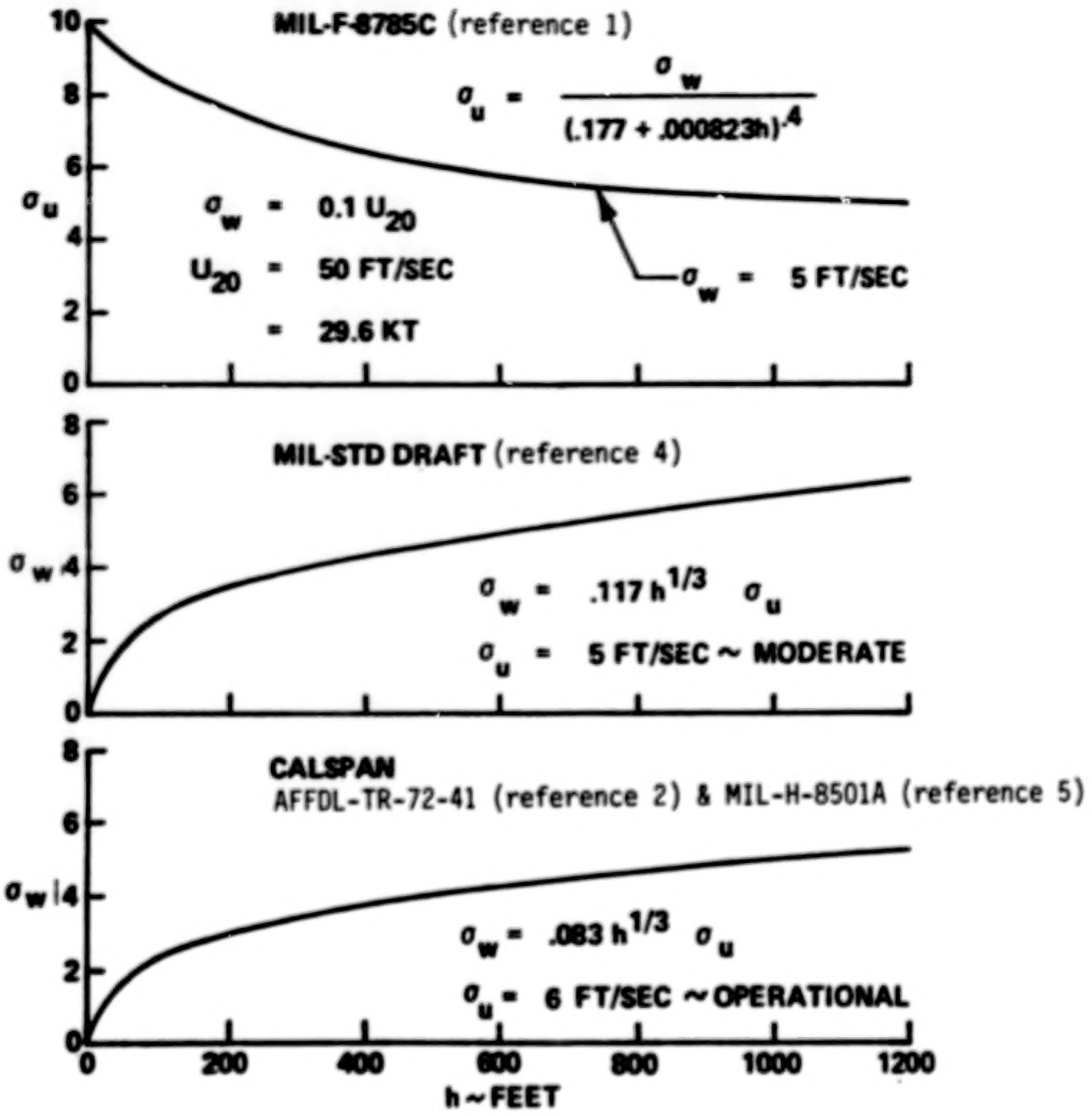


Figure 4. Dryden Model Scales and RMS Intensities.

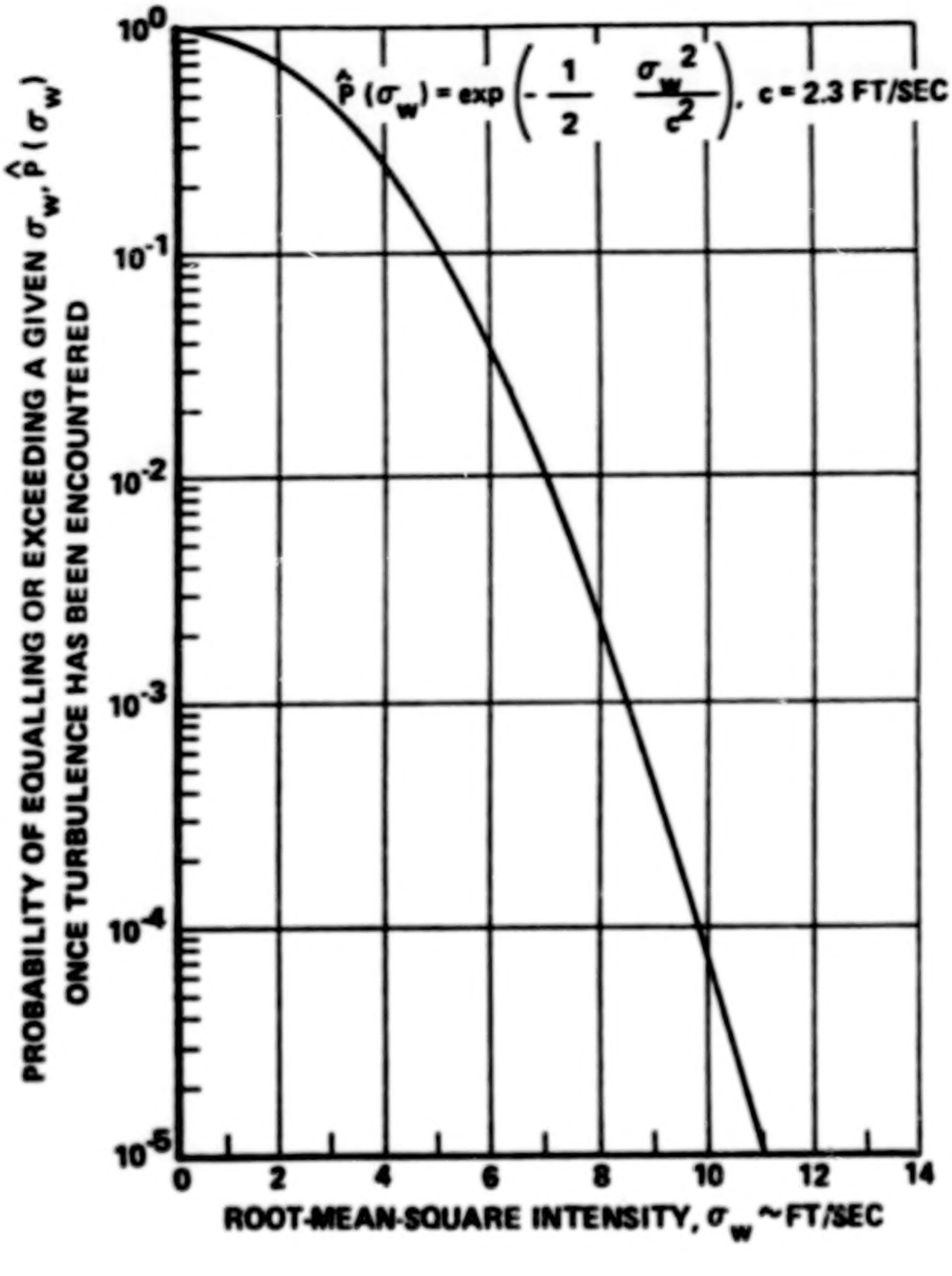


Figure 5. Probability of exceeding a given σ given that turbulence is encountered.

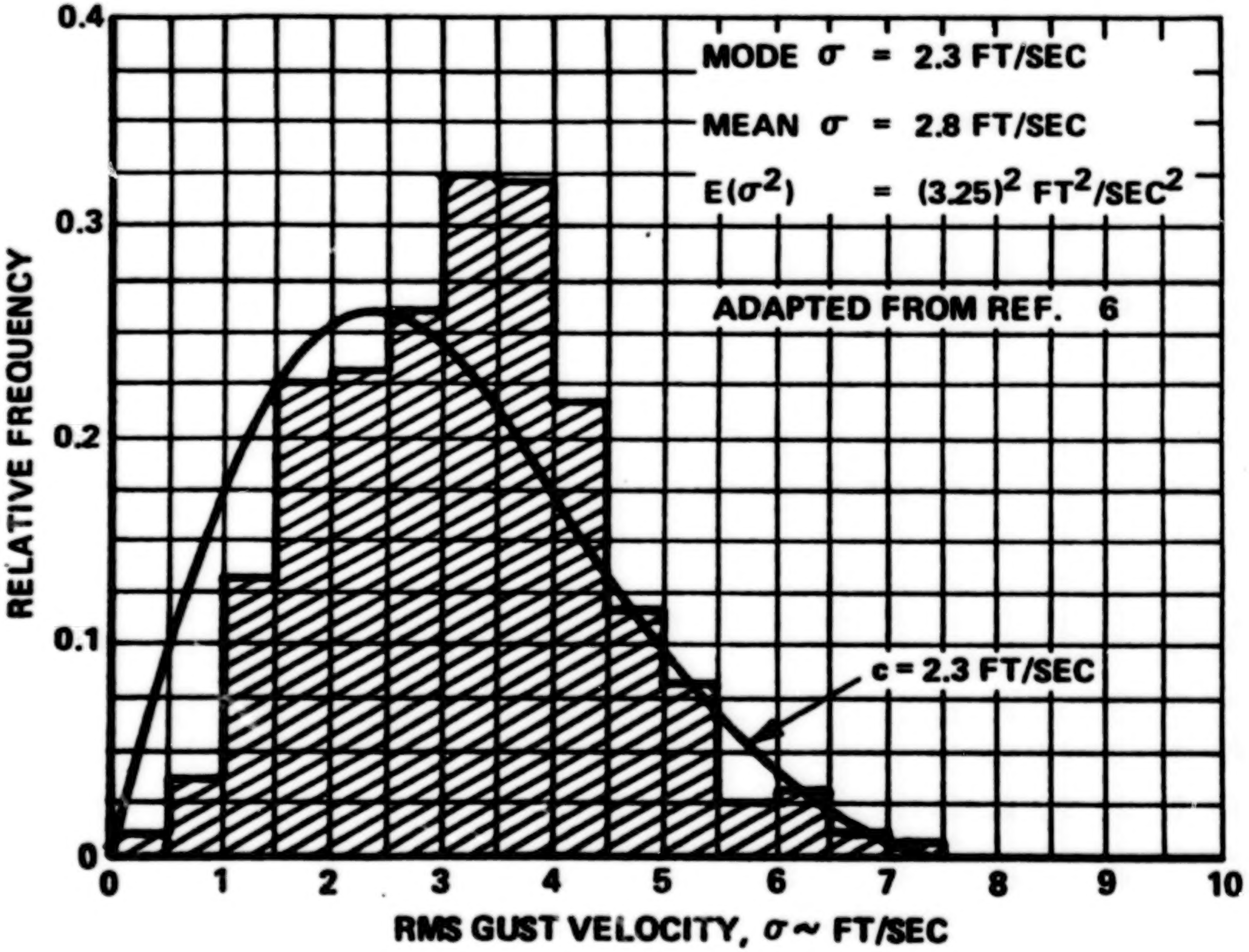


Figure 6. Relative Frequency Distributions of RMS Gust Velocity from B-66 Low-Level Program.

MIL-F-8785B	LOW ALTITUDE (reference 7)
CLEAR AIR	σ_w = 6.7 FT/SEC
THUNDERSTORM	= 21 FT/SEC

MIL-F-8785C	LOW ALTITUDE	MEDIUM/HIGH ALTITUDE (reference 1)
$\sigma_w = .1\ U_{20}$	σ_w	σ_w $h = 10$ KFT
LIGHT (WIND)	2.53 FT/SEC	5 FT/SEC
MODERATE	5.07	10
SEVERE	7.61	21

BRITISH AvP970 (reference 8)	
LIGHT	σ_w = 3 FT/SEC
MODERATE	5
HEAVY	10
EXTREME	20

MIL-STD DRAFT (reference 4)	
LIGHT	σ_u = 3 FT/SEC
MODERATE	5
SEVERE	10
EXTREME	24

CALSPAN	$h < 1750$ FT	$h > 1750$ FT
ENVIRONMENTS	σ_u	σ_u
OPERATIONAL	6 FT/SEC	6 FT/SEC
MOST SEVERE	10	20

Figure 7. RMS Turbulence Characterizations.

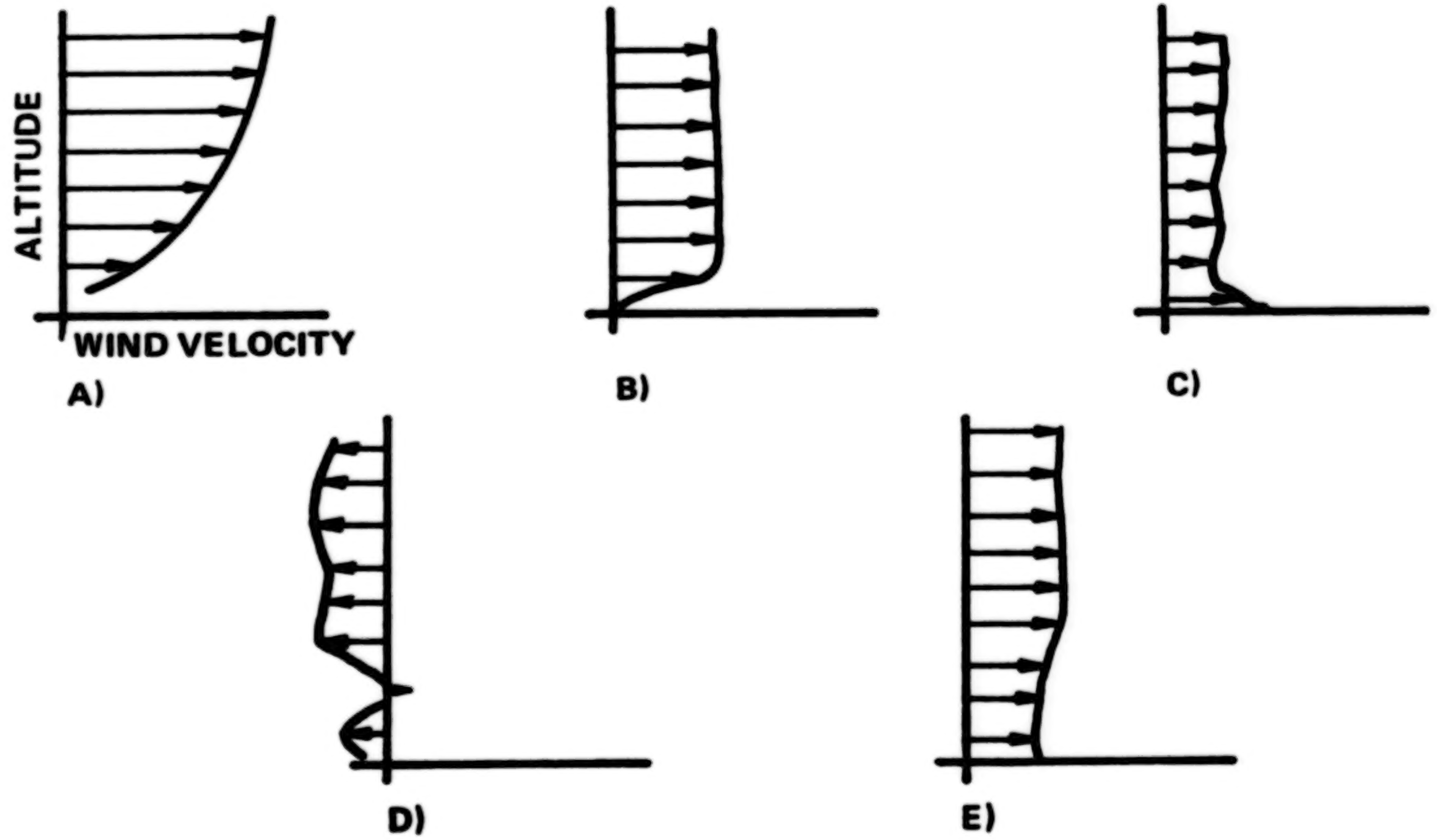
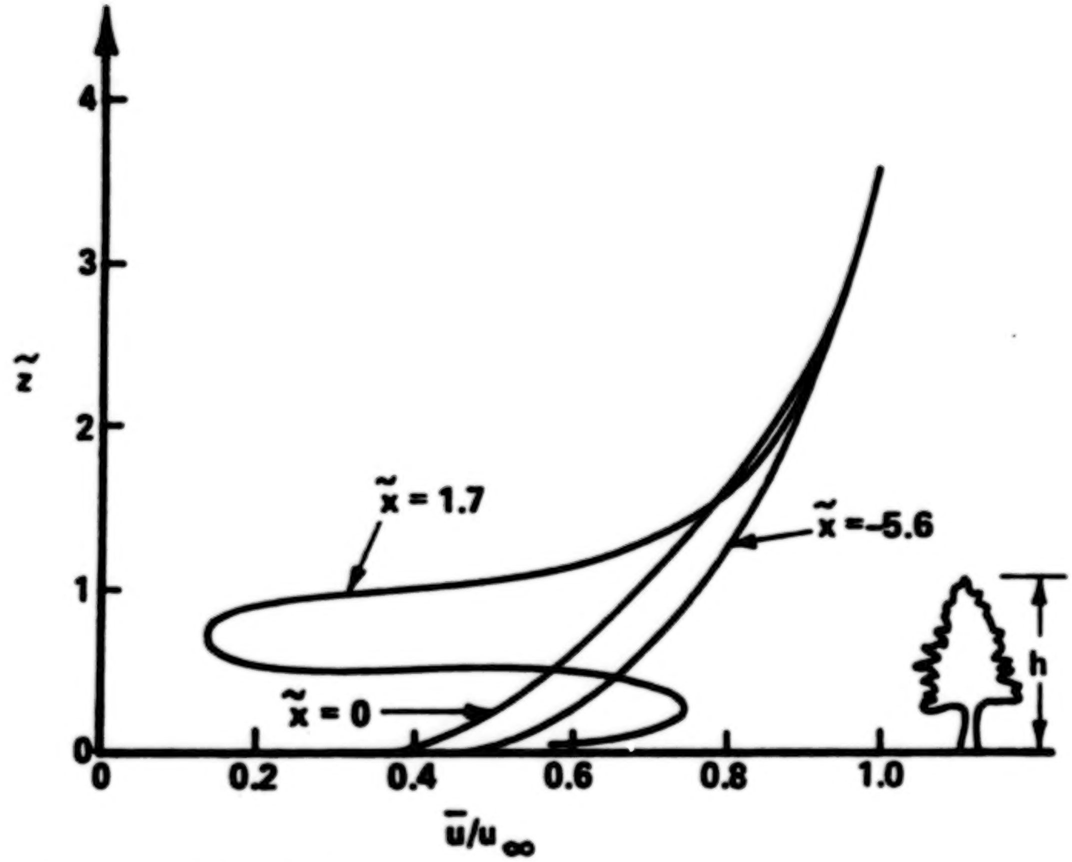

ALTITUDE
WIND VELOCITY
A)
B)
C)
D)
E)

Figure 8. Representative Wind Shears.



h = HEIGHT OF TREES

x = HORIZONTAL DISTANCE DOWNWIND OF EDGE OF FOREST

$\tilde{x}$ = x/h

z = HEIGHT ABOVE FLOOR OF FOREST

$\tilde{z}$ = z/h

$\bar{u}$ = LOCAL MEAN VELOCITY

u_∞ = REFERENCE VELOCITY AT REFERENCE HEIGHT WELL ABOVE FOREST CANOPY

Figure 9. Normalized Velocity Profiles Near the Edge of a Forest--Showing the Jetting Action in the Region of the Trunks--Tree Spacing ≈ h.

turbulence, you require the capability. In severe turbulence, the capability is not required. This leads to a different design requirement on the flight control system in heavy turbulence. You can have a requirement for a level-three airplane or a level-two airplane in very heavy turbulence. This may end up designing the flight control system, whereas requiring level one in light, or no, turbulence may not be the critical design point.

QUESTION:

With regard to the change in velocity that you just talked about, one way of interpreting that is that it requires the level-three airplane in a sense to be as good as the level-one in severe turbulence. Is that realistic?

RESPONSE:

If an airplane is level one in clear air, no turbulence, what we are suggesting is that you would allow it to degrade to level two or three in moderate to heavy turbulence, and still satisfy the spec. However, you would not call it a level one airplane in that situation.

QUESTION:

If the airplane was in what otherwise was considered to be a level three situation, you still have a required capability to satisfy it with severe turbulence...if it's level three for other reasons. Now, in addition, if you have severe turbulence, this is more restrictive in some sense.

RESPONSE:

Yes, it could end up designing the airplane. In fact, there are some instances where they should have looked at heavy turbulence in the design because the airplane is almost unflyable in turbulence. If you look at smooth air and look in the simulator without exercising this area, you will design a dangerous airplane.

Table I. Definition of Levels When Levels Are Defined by Cooper-Harper Rating Scale.

LEVEL	ATMOSPHERIC DISTURBANCES			
	LIGHT	MODERATE	SEVERE	EXTREME
1	3-1/2	5-1/2	7-1/2	Flying qualities such that control can be maintained long enough to fly out of the disturbance.
2	6-1/2	7-1/2	Flying qualities such that control can be maintained long enough to fly out of the disturbance.	Flying qualities such that pilot can regain control after being upset.
3	9-1/2	Flying qualities such that control can be maintained long enough to fly out of the disturbance.	Flying qualities such that pilot can regain control after being upset.	No requirement

Table II. Minimum Operational Capability Required .

LEVEL	LEVEL DEFINITION	ATMOSPHERIC DISTURBANCES		
		LIGHT	MODERATE	SEVERE
1	Flying Qualities Clearly Adequate for the Mission Flight Phase.	Required Capability	Capability Not Required	Capability Not Required
2	Flying Qualities Adequate to Accomplish the Mission Phase, but Some Increase in Pilot Workload or Degradation in Mission Effectiveness, or Both, Exists.	Required Capability	Required Capability	Capability Not Required
3	Flying Qualities Such That the Aircraft Can Be Controlled Safely in the Mission Flight Phase, but Pilot Workload is Excessive or Mission Effectiveness is Inadequate, or Both.	Required Capability	Required Capability	Required Capability

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UNRESOLVED ISSUES IN WIND SHEAR ENCOUNTERS

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ABSTRACT

Much remains to be learned about the hazards of low-altitude wind shear to aviation. New research should be conducted on the nature of the atmospheric environment, on aircraft performance, and on guidance-and-control aids. In conducting this research, it is important to distinguish between near-term and far-term objectives, between basic and applied research, and between uses of results for aircraft design or for real-time implementation. Advances in on-board electronics can be applied to assuring that aircraft of all classes have near-optimal protection against wind shear hazards.

INTRODUCTION

While the earth's atmosphere provides a medium within which fast point-to-point travel is possible, it also challenges that travel through various meteorological phenomena. The principles of aircraft motion in a quiescent air mass are well understood; given accurate mathematical models of inertial, aerodynamic, and thrust characteristics, these motions can be predicted precisely, and both manual and automatic procedures for guidance and control are straightforward. Unfortunately, the atmosphere is rarely quiescent; winds and rain provide major (potentially life-threatening) disturbances to aircraft motion [1]. While meteorological trends are predictable to some extent, the four-dimensional nature of the air mass, existing as it does in space and time, makes deterministic prediction of these disturbances difficult, if not impossible. Consequently, aeronautical operations are conducted with a high degree of uncertainty about the disturbance environment.

Reducing the uncertainty associated with air travel can be considered an unifying factor of research programs dealing with the wind shear hazards. Still, it must be recognized that there is a diversity of objectives and approaches. Some research focuses on the atmosphere, while other work concentrates on the aircraft. These programs can be further divided into those that seek to increase the knowledge base for design and planning and those that address real-time operations and control. An additional dimension is added to the classification by the intended time frame for application of results; it is desirable to increase the near-term protection of existing aircraft against the wind shear hazard, but it is also important to investigate concepts for long-term improvements in aircraft, systems, and operational procedure.

The remainder of this paper addresses unresolved issues in three areas of technical knowledge regarding wind shear hazards to aircraft. The first deals with the atmospheric environment, which works both for and against the aircraft, and which is unaffected by human intervention. Microbursts, which are unusually severe downdrafts accompanied by intense outflows, can be especially hazardous. The second relates to aircraft dynamic response, which can be modified by design,

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to some extent, for maximum realizable protection against the hazard. The third area is guidance-and-control aids, which offer the opportunity to use available performance in an optimal way for wind shear penetration or avoidance.

While the most prudent approach is to avoid hazardous meteorological conditions whenever possible, there always will be those borderline cases in which pilots are called upon to weigh hazards against mission objectives. Because the future is uncertain, there will be instances when the pilot presses on even though hindsight will prove that to have been the wrong choice. The issues raised here relate principally to the identification of these borderline situations and to safe flight in hazardous conditions.

ATMOSPHERIC ENVIRONMENT

The atmosphere exists in three spatial dimensions, and its characteristics vary in time. These characteristics include scalar quantities (pressure, density, humidity, and temperature), the wind vector, and contaminants, e.g., rain, insects, and dust. The scalar quantities normally vary over large space and time scales, and the contaminants often are "patchy", i.e., there are discrete changes in otherwise uniform distributions of these elements. The wind vector contains both steady and unsteady components; it is customary to distinguish between a mean component, which varies slowly in time and gradually in space, and a perturbation component (turbulence and gusts) that changes quickly and over short distances.

Relative to the standard atmosphere, variations in all of these quantities can be considered potential disturbances to aircraft flight. The slow, long-wavelength disturbances can be accommodated by changes in trim settings and operational procedures. These are amenable to synoptic prediction, so pilots have advance warning and can plan accordingly. The fast, short-wavelength disturbances are much less predictable. They constitute hazards to flight when their magnitudes are sufficient to cause extreme deviations from the flight path or to overstress the aircraft. The extent of the hazard depends upon the flight condition, the aircraft's structural and aerodynamic integrity, and the control policies that are employed during the encounter.

Frozen Wind Profiles and Statistics of Uncertainty

Because the wind vector is three-dimensional, there are nine terms in the wind shear gradient with respect to spatial coordinates, as well as three terms in the wind's time-derivative. Although it is often satisfactory to idealize an aircraft as a point mass for dynamic calculations, an aircraft's size plays a role in determining its response to wind shear gradients--for example, a spanwise gradient in the vertical wind produces a rolling moment that would not appear in the equations of motion written for a constant wind field.

Response to the wind shear gradient and time-derivative should be distinguished from response to the wind velocity itself. The former contributes principally to aeroelastic response, while the latter has more direct effect on an aircraft's flight path response. A spanwise gradient such as that mentioned above could be an exception, in that rolling response integrates into net heading changes that must be corrected to maintain the intended flight path. Even though the wind field has a spatial distribution, this is transformed into a temporal distribution by an aircraft's transit through the wind field. Consequently, temporal and spatial variations become indistinguishable along a given flight path--at least from the standpoint of an aircraft's dynamic response.

It should be possible, therefore, to specify frozen spatial distributions (with sufficient resolution to derive gradients) that could be used in flight simulation to represent the disturbance environment. The mass of data collected in the Joint Airport Weather Studies (JAWS) and related programs could be used to specify time-invariant wind fields in a variety of useful formats. One such format would be a series of wind fields possessing distinctive features that are potentially hazardous and that are differentiated by varying intensities and length scales. Another would be a range of statistics, e.g., probability density functions and spectra at various confidence levels, indicating the uncertainties associated with the disturbance inputs that an aircraft would experience on paths through these wind fields.

It would be particularly useful to assess spatial correlations in the more hazardous wind fields. Given a certain wind intensity, how likely is it that conditions will be worse 500 or 1000 or 1500 feet ahead of the aircraft? Are there patterns that signal especially hazardous conditions?

Pressure and Temperature Variations in Microbursts

Although attention has been focused on the adverse effects of tail winds and downdrafts, unusual local variations in ambient pressure and temperature could have detrimental effects as well. Most aircraft rely on air data--at least in part--to determine altitude, airspeed, and rate of climb or descrnt. Warnings and guidance strategies for abort or penetration would make use of such data, so it is important to know whether or not there are meteorological factors that would degrade these data on the time scale of aircraft motions.

Correlation of Wind Shear with Heavy Rain

Although microbursts can occur in dry weather, hazardous wind shears often are accompanied by heavy rain. Heavy rain can have two dangerous effects. First, it can affect combustion in turbine engines; engines have been quenched by heavy rain, an unacceptable alternative for either takeoff or landing. Second, it can degrade the aircraft's lift, moment, and drag characteristics. Although much wind-tunnel testing remains to be carried out, even modest changes in lift-drag ratio or pitching moment characteristics could have major impacts on aircraft performance and controllability. The combination of adverse wind-shear and heavy rain effects could be much worse than the effects of either phenomenon alone; therefore, it is important to understand the interrelationships between the two.

AIRCRAFT DYNAMIC RESPONSE

Aircraft are configured to achieve mission objectives subject to design constraints. Underlying the design process are considerations of effectiveness, pilot workload, life-cycle cost, maintainability, comfort, and safety. Although most aircraft are optimized for one or more mission profiles, the wide diversity of configurations that are ostensibly designed to satisfy similar criteria attests to the allowable freedoms in aircraft design. These differences can be attributed to differences in the value placed on opposing design objectives, as well as to differences in the styles of competing airframe manufacturers. Thus, competing aircraft can be considered "optimal" in some sense, even though one has better specific fuel consumption, another has lower direct operating costs, another has better flying qualities, and so on.

It is unlikely that wind-shear penetration characteristics ever will become major drivers in configuration design, but better understanding of these characteristics could identify factors which would reduce the wind shear hazard while satisfying principal objectives. Greater attention to aerodynamics of the stall region is an obvious example of this point. Both longitudinal and lateral-directional aerodynamics are of concern--an otherwise benign stall break could become disastrous if accompanied by divergent roll-spiral oscillations or loss of lateral control. In addition to the usual effect on pitch damping, tail-lag aerodynamics could produce unexpected response to vertical wind inputs. The heavy-rain effects mentioned above could impact the selection of airfoil sections and the design of engine inlets.

Edges of the Envelope

For given aircraft configurations, the limiting magnitudes and profiles of horizontal and vertical wind inputs should be determined. While static or quasi-static response to shears of fixed value are of interest, wind-shear encounter is a dynamic event. Correspondences of elevator and throttle trim settings to fixed changes in the wind must be understood, but the dividing line between safe and unsafe encounter is affected by the phasing of control inputs, as well as by the "stored" energy and momentum (both translational and angular) at the time of encounter. Static analyses are not necessarily conservative, nor do they reveal the full potential for successful wind-shear penetration.

The "edges of the envelope" can be defined using trajectory optimization or reachable-set evaluation. These involve accurate mathematical models of the aircraft combined with flight-path simulation and search algorithms. A distinction is made between these analyses and simulation to identify piloting procedures or control system designs. The purpose is to understand what the aircraft's true limits are, establishing standards against which further developments can be evaluated.

Control Power and Flying Qualities Requirements

An aircraft's control "power" usually is described by the maximum available angular accelerations that result from full deflection of its control surfaces; however, a broader definition is implied here. In the context of wind-shear encounter, thrust, lift, and drag controls also should be considered, and it is necessary to address the time lags associated with control actuation. It is easy to postulate fast-acting, high-force effectors that would counter wind effects, but it is not known if such effectors are practical, necessary, or even effective.

Control and power requirements for elevator, ailerons, and rudder already address important elements of control against the wind, and it seems appropriate to develop similar insights about the possible utility of flaps, spoilers, drag brakes, and thrust augmentation. Making an approach with partially deflected spoilers, for example, would afford a measure of "instant L/D" on wind-shear encounters; aside from current operational objections to such a procedure, it is not obvious that the incremental lift increase and drag reduction would materially aid flight path management during encounter. If, however, the spoilers could be effective in this role, consideration should be given to the design and operational changes necessary to effect such control. Similarly, the value of optimal direct-lift control via flaps should be determined.

Current flying qualities requirements address both fast and slow response characteristics of aircraft, although the former have received greater attention in recent research. Nevertheless, it is the latter that have the more significant relationship to wind-shear response. It would be appropriate for flying qualities specifications to reflect the impact of phugoid- and spiral-mode stability on an aircraft's response to wind-shear inputs, as these modes can be very lightly damped, even slightly unstable in some circumstances. Because the time scale of a microburst encounter may be of the same order as the phugoid-mode period, a resonant response is possible; this amplifies the resulting interchange between kinetic and potential energy, which is to say there is a greater deviation from the nominal flight path than would occur with a well-damped mode.

There must be greater concern for high-angle-of-attack flying qualities, not only for maneuvering high-performance aircraft, but for aircraft of all classes. Exposure to high angle of attack and unusual attitudes is likely during wind-shear encounter. A departure-from-controlled-flight during takeoff or in the landing pattern would be catastrophic. The classic symptoms of inertial coupling during rolling pullups, loss of roll damping near the stall, and degraded control effectiveness all can be experienced by jet transports, general-aviation (GA) aircraft, and helicopters during wind-shear encounter.

General Aviation Aircraft and Helicopters

Tragic accidents involving commercial jet transports encountering wind shear have focused attention on the subject, but small aircraft are at least as (if not more) susceptible to windshear-induced accidents. Because their inertial and aerodynamic characteristics are so different, wind fields that are hazardous for one aircraft type may be less hazardous for another type. The principal distinctions are due to airspeed and wing loading, i.e., the aircraft weight divided by the wing area. Aircraft with high airspeed and wing loading appear to be more sensitive to gradients in head/tail wind, while aircraft with low airspeed and wing loading are more adversely affected by downdrafts [2]. Trajectory deviations are extreme when the disturbance input's wavelength is close to the aircraft's phugoid-mode wavelength. Since the phugoid-mode wavelength is proportional to the square of the forward speed, a wind profile that resonates one aircraft type may not resonate another. Consequently, it is difficult to generalize about the atmospheric conditions that constitute a hazard to aviation in general.

The possibilities of dangerous wind-shear encounter for GA aircraft and helicopters are exacerbated by the circumstances of their use. First, they are more susceptible as a consequence of low airspeed and wing (or rotor-disk) loading. They often are flown out of unimproved airfields with minimal meteorological instrumentation and terrain-induced wind shear. Helicopters often are used on emergency or otherwise urgent missions in poor weather, so frequency of exposure to hazardous wind shear is relatively high.

Because the cost of equipment is so much lower, because the operators of such aircraft routinely accept the risks, and because the potential loss of life (per accident) is less, few studies of the wind-shear hazard to GA aircraft and helicopters have been conducted. Furthermore, when amateur or low-time pilots are involved, it often is concluded that "pilot error" is the probable cause; hence, accident statistics may not give an accurate portrayal of the extent of the wind-shear problem. Nevertheless, the potential severity of the consequences suggests that added attention should be given to the unique wind-shear encounter problems of these classes of aircraft.

GUIDANCE-AND-CONTROL AIDS

Perhaps the most treacherous aspect of wind-shear encounter is that counter-intuitive piloting may be the key to survival. With the onset of strongly increasing tail wind or decreasing head wind, an aircraft loses airspeed and, therefore, lift. The pilot's normal reaction of adding power is appropriate, but the time for thrust to build and for this to integrate to increased airspeed and lift may exceed the time available for recovery. In such instance, the only way to increase lift quickly is to increase the angle of attack; however, raising the nose in response to decreasing airspeed is contrary to everything that the pilot has learned for flight in constant-speed air masses. This training effect is so strong (and so right under normal circumstances) that it is unrealistic to expect pilots to pull the nose up without added information and guidance.

Of course, the pilot's principal worry is that the aircraft will stall, but stalling represents the maximum amount of lift that can be squeezed out of the aircraft at a given airspeed. The trouble is that airspeed or altitude or both decay rapidly if the stall angle of attack is held for any length of time, lateral-directional flying qualities may be unfamiliar if not unacceptable, and visual ground contact may be lost at high pitch angle.

Successful wind-shear penetration may require a higher level of airmanship than could be expected from the average pilot unless proficiency can be maintained through continual practice in high-fidelity ground simulators. (Even then, there is some question about the value of simulation, as exposure to one wind shear profile may provide negative training for an equally hazardous but different profile.) With the understanding that wind-shear encounters are rare but violent events, the practicality and cost-effectiveness of keeping all pilots current in the proper procedures is questionable.

A better approach is to assure that pilots receive adequate warning and real-time guidance when the wind shear occurs. Modern instrumentation and avionics make various levels of protection against the wind-shear hazard possible for all classes of aircraft. Instruments that sense vertical acceleration or specific energy rate (the rate-of-change of kinetic and potential energy, divided by aircraft weight) are available; with proper desplays, they can indicate that the aircraft has penetrated wind shear and can give rudimentary guidance for evasive action. An angle-of-attack display can let the pilot maneuver up to the stall with increased confidence.

At the next level of sophistication, multisensor packages plus minimal amounts of computer logic can sense wind shear with increased reliability and can issue visual or aural warnings. Integrating such information into the logic that drives an advanced flight director provides more specific guidance for penetration of mild wind shears and for abort in severe wind shears. The same signal that drives the flight director can drive an auto-takeoff or auto-land system; this removes the pilot from the "inner" control loop, which may or may not be desirable.

Optimal Trajectories and Control Laws

While there is an increasing body of "folklore" regarding the "best" control strategies for wind-shear penetration or avoidance, there is a singular lack of hard information regarding the subject. It would be useful to know not only where the "edges of the envelope" lie but what the optimal control strategies are.

Two classes of optimality are of interest. Deterministic optimal trajectories and control histories for specific wind profiles would furnish insights about the phasing and magnitude of control inputs, and they could identify the relative value of initial condition variations, e.g., the "airspeed pad" or height above the nominal glide slope that would be necessary for successful encounter. It is conceivable that a guidance law based on dynamic programming could use pre-computed trajectories and controls in real time, although the practicality of such an approach must be determined.

Nevertheless, wind-shear encounter is a random event, and it seems likely that stochastic optimal control laws would provide increased margins of safety. In this approach, prior knowledge of aircraft dynamic characteristics and of the statistics of the disturbance environment and measurement uncertainties is combined to maximize the expectation of safe passage. The better the knowledge of the wind field, the more effective the stochastic optimal control will be. The mathematical tools for implementing optimal control laws in real time exist; it remains for them to be applied to the problem.

Predictive Estimates of the Wind

Of course, the problems of guidance and control would be reduced materially if there could be some detailed knowledge of the wind field before the aircraft enters it. Because the wind field is varying in time, there always will be some uncertainty about the disturbances that the aircraft will experience, but wind measurement that is predictive in some sense could reduce the uncertainty.

Here, "predictive" simply means that an estimate of the wind field exists prior to encounter; a measurement that is a few seconds old is itself a prediction which could be improved by taking account of time and space correlations. The wind sensors could be located either on the ground or in the aircraft, and there are many pros and cons to each approach [1]. For warning and avoidance, current estimates of the wind field that are one to five phugoid wavelengths ahead of the aircraft would provide enough time to frame guidance strategies, and they probably would be sufficiently "fresh" for making "go-no go" decisions. This corresponds to wavelengths of about a quarter to one nautical mile for GA aircraft and about five times that for jet transports. Corresponding lead times for GA aircraft are about 15 seconds to one minute and one-half to two-and-a-half minutes for the jet transport. For control during penetration, current wind estimates should extend from one to five short-period wavelengths ahead of the aircraft, roughly reducing the above numbers by a factor of five.

Predictions of the uncertainty of the wind as well as of the wind itself are useful. If the wind shear is predicted to be too great on the glide slope, that is grounds for abort; however, if the predicted uncertainty in wind inputs exceeds the aircraft's capabilities, that also provides a reason for go-around. Given such predictions, it would be possible to compute a projection of the desired nominal path; the desired path could be generated using concepts of "dual control", which combine prediction with optimal estimation and control.

Application of Artificial Intelligence

The computer power that can be packaged economically for use in flight has reached the point that artificial intelligence (AI) methods could be applied to the guidance-and control problem. In engineering application, AI generally refers to the process of making a computer emulate the rational behavior of a human expert.

In the context of wind-shear encounter, "DI methods" can be interpreted as storing all rational policies for pilot response to wind shear and retrieving that information which is appropriate for the case at hand. It also might connote decision-making and presentation of alternatives to the pilot, including alternatives for manual or automatic control. Behaving like an intelligent advisor to the pilot, the AI logic for the flight computer would provide an interface between the optimal control laws suggested above and strategic planning of the aircraft's flight.

CONCLUSION

Wind shear is not a new phenomenon, but there is heightened interest in minimizing the hazard it presents to aircraft of all classes. This is the result of many factors, not the least of which is that technical solutions to the problem are becoming more practical as a consequence of continued meteorological, aeronautical, and electronic research and development. Furthermore, there is increased awareness that aviation safety is not only humanitarian but that it constitutes a direct benefit to our society. While there are important unresolved technical issues, approaches to resolving many of these issues can be identified. What remains is the commitment of sufficient resources to turn these solutions into reality.

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SIMULATOR SYSTEMS INTEGRATION

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INTRODUCTION

This paper will discuss the implementation of available wind shear data into general aviation flight training simulators.

Currently, we have 11 simulators with wind shear models installed involving some nine different aircraft models. Retrofits to other systems that we put out earlier are currently under way, and of course, all the new simulators we put out will have wind shear available for the instructors to use for demonstrations and training. We have three types of computer systems involved through all of this, and two different types of instructor stations. Most of the systems we have with wind shear, to date, are the CRT-type displays. Our older simulators involve a mechanical station which requires digi-wheels for wind shear numbers and an activation button of some type. This means that a little bit of hardware change as well as software load is required to get wind shear working in systems that have been in service for some time. We've used the 10 SRI profiles that we received some years ago, which basically involves a two-dimensional table lookup process.

The first application we had was to a Bell 222 helicopter which happened to be using a high-speed computer that was specially designed for table lookup; we took the brute-force approach there. It computes the wind shear components for all 10 shears all the time. When the instructor selects one, a non-zero multiplier is applied to make that wind shear profile come into effect.

The other systems for the fixed-wing aircraft involve a PDP 11/55 computer; and a little more sophistication, if you will, had to be incorporated to make wind shears usable. When the selection is made of a wind shear on these systems, a particular file is pulled off disk and then utilized. So more interface was needed with the instructor, hardware, and so forth. The G-III happened to have the same computer system as the Bell 222 and used, again, the brute-force method. The other simulators coming out are, by and large, Perkin-Elmer computers using Fortran. We are currently at the stage of getting the wind shear operations checked out and functional so the data can be loaded into simulators that are on the floor now and coming out to go into training.

Essentially, the mode of operation is that the instructor selects a certain profile that he wants to use on this approach and we require that the ILS be tuned into the NAV 1 receiver. The purpose for this is that existing NAV calculations could provide the reference point and runway heading to be used for the wind shears. Usually the approaches are made down an ILS, so making winds dependent upon navigation doesn't really represent much restriction. It's bad enough that they are dependent on aircraft accident investigations which back out estimates of wind from aircraft response. Then, of course, the simulator must be flown within range (distance and altitude) of the data base we have in order to have these winds occur.

As for the equations of motion, I've just listed the process we go through. Basically, we operate in the inertial frame system. Assuming we start with the point where we can calculate forces and, consequently, accelerations in the body axis, then we are in a position where these body axis accelerations can be transformed to earth axis and, then, integrated to get earth axis or earth frame velocities for the aircraft itself. At that point, the wind components, which are in the earth reference frame, can be added. When that is done, we can transform the summation of airframe and wind speeds back through the Euler angles to the body axis and thereby calculate angle of attack, side slip, total velocity, dynamic pressure, Mach number, etc. This then provides the inputs through which the aerodynamic coefficients can be calculated then multiplied by dynamic pressure to generate the forces used when going back through the loop. So, the inputs for wind come in as a straight linear addition to airframe velocity in the earth axis and they show up then through the aerodynamic forces only by their transformation back to body axes for the relations for the relations for α, β, etc.

We have assumed through this that the airframe is a point mass and that the wind is composed of three linear components acting at that point. No time variation on the wind is considered. We use turbulence to get something when conditions are desired to be a bit rough. This might look like it would present a problem if you hovered a helicopter at any given location on the approach. Then, there would be no wind shear because the winds would be constant at that point as far as the time variation that the pilot is seeing.

As for turbulence, we operate with white noise from a random number generator, and perhaps a first-order filter on that, without getting into too much detail with Dryden turbulence processing of that white noise. We'd like to see some studies done on research simulators concerning what the significance of turbulence modeling is to handling qualities evaluations, and what model is then worth installing for training. The amplitude of the turbulence is really carried as a constant which is under instructor control. Making that part of the wind shear approach would probably be the next step in refining or developing our operations here.

Some of the refinements which might be worth considering would be to provide aerodynamic moments due to linear wind variation (this is our wind shear slope, if you will), since a spanwise variation is essentially equivalent to a roll rate that will produce a roll damping moment, and perhaps then to get wind shear and turbulence terms put into the $\dot{\alpha}$ and $\dot{\beta}$ calculations. We have some use for $\dot{\alpha}$ calculations in flight dynamics; $\dot{\beta}$ is more prevalent, although it's on the order of one-fourth (or less) that of pitch rate damping. Finally, the Dryden turbulence equations, or perhaps von Karman or some type which are easy to program, implement, and checkout, could be put under consideration.

From a brief check on some of the experience we've had with wind profiles, we do find to some extent that fixed profiles can be learned rather quickly. If you go through the trip another one or two times, there will no longer be a lack of surprise about where and how the wind shear will occur, and this is felt to be rather unrealistic. However, in practice, the pilot who is in for initial or recurrent training is only going to encounter one or perhaps two wind shear approaches during the week or two that he is there. After all, wind shear can be considered one weather malfunction, and there are up to 150 other types of aircraft malfunctions that have to be covered in this span of time. Wind shear is on the syllabus and is something that will be shown to the student, but it is not something that they run through enough times to gain a lot of experience on where and how this wind shear will occur. Our weather cues come from the visual system in terms of visibility and so forth, and are controlled strictly by the instructor. Coordinating wind shear maps with visibility is not considered to be an important thing to try to implement. Clear air turbulence obviously exists and things like microbursts may occur more in clearer conditions than they would when breaking out from under the clouds.

The student may be a bit too successful at recovery during a wind shear encounter in a simulator. First of all, when they go into a session, they are briefed concerning what types of things they are going to see during the two- to three-hour session on the simulator; they will, thereby, be anticipating wind shear and looking for the symptoms that would occur in terms of airspeed, altitude, and so forth. The students then may come up with quicker recognition and recovery in the simulator than they might have during actual weather and aircraft practice. Our concern to some point is that this success and recovery may encourage flight into wind shear when, in fact, it should be avoided.

New data bases that would be useful at this point would be profiles for takeoff. Perhaps the SRI profiles could be modified to set up a takeoff operation. Obviously, the microburst will be a good one that can be applied if we get a profile to operate at the takeoff end of the runway. It looks as if the microburst, or the JAWS data, would provide a good model to add or maybe even replace some of the calm SRI profiles we now have that see little use. The three-plane data for corridors from the JAWS data looks as if it could provide a good lateral dimension as an expansion to our current two-dimensional operation and might well be worthwhile.

Finally, how turbulence is modeled and how much it is worth in terms of programming time to implement it, and computer time to run it, will depend largely on how much difference the pilot would see in the simulator affecting handling qualities and touchdown accuracy.

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HELICOPTER-V/STOL DYNAMIC WIND AND TURBULENCE DESIGN METHODOLOGY

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INTRODUCTION

Aircraft and helicopter accidents due to severe dynamic wind and turbulence continue to present challenging design problems. The development of the current set of analysis tools for aircraft wind and turbulence design began in the 1940's and 1950's and remains today a developing field. The areas of helicopter dynamic wind and turbulence modeling and vehicle response to severe dynamic wind inputs (microburst type phenomena) during takeoff and landing remain as major unsolved design problems from a lack of both environmental data and computational methodology.

This paper will review the development of helicopter and V/STOL dynamic wind and turbulence response computation methodology, outline the current state of the design art in industry, and comment on design methodology which may serve to improve future flight vehicle designs.

DIFFERENCES BETWEEN AIRCRAFT, V/STOL, AND HELICOPTERS

A review of recent literature provides an interesting comparison of V/STOL, helicopter, and aircraft flight characteristics and design methodology. Gust response of helicopters with lifting rotors, rotary-fixed wing aircraft, and large diameter propellers in V/STOL and tilt rotor aircraft is discussed in [1]. He notes that the major difference between conventional aircraft and rotary wing-propeller gust wind response modeling in forward flight is that even with stationary turbulence velocity input to rotor blades, the resultant vehicle response is nonstationary because of the gust front encounter with blades at various azimuth positions.

Thus, even the simplest gust statistical analysis for the rotary wing vehicle is fundamentally nonstationary and substantially more complex to analyze than a comparable aircraft problem. Gaonkar points out that three criteria establish feasibility of the nonstationary problem analysis as follows:

1. Taylor's hypothesis holds.

2. Gust fluctuations are Gaussian although nonstationary.

3. Helicopter rotor gust excitations can be idealized as a separable nonstationary process composed of a conventional stationary gust field modulated by the deterministic rotor transfer characteristics.

For the case of hovering helicopters, Lakshmikantham and Rao [2] computed rotor blade turbulence response utilizing conventional linear, stationary turbulence theory. Computational results were obtained for hinged and wingless rotors.

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Judd and Newman [3] analyzed helicopter rotor response to gusts and turbulence and concluded that current articulated and semi-rigid rotors are insensitive to in-plane gusts. Vertical gust sensitivity is relatively independent of forward speed and inversely proportional to blade loading (not disk loading), whereas aircraft gust sensitivity is proportional to forward speed and inversely proportional to wing loading.

Reichert and Rade [4] concluded that helicopters, with their relatively low disk loading, are sensitive to gusts when compared with aircraft; that disk loading is the major design parameter affecting turbulence; and that gust-induced structural loads are less important for design than maneuver-induced gusts.

In 1972, Elderkin et al. [5] noted in the TOLCAT report that both aircraft and V/STOL flying at high velocity and moving in the direction of the mean wind see atmospheric turbulence modeled by

$$\left.\frac{\partial u_i}{\partial t}\right|_a = - \bar{U}_a \frac{\partial u_i}{\partial x_1}$$

with the aid of Taylor's hypothesis (the variation of turbulence seen by the aircraft is linearly related to the variation of turbulence in the longitudinal direction). However, the hovering helicopter sees a turbulent eddy motion which satisfies

$$\left.\frac{\partial u}{\partial t}\right|_a = - u_j \frac{\partial u_i}{\partial x_j} - \frac{1}{\rho} \frac{p}{x_i} - r \frac{\partial^2 u_i}{\partial x_k \partial x_k} + g \frac{\theta}{\Theta} \delta i_3.$$

Here the turbulence seen by the aircraft is related to spatial turbulence in a nonlinear manner. Thus, the helicopter in hovering or slow-speed flight presents a significantly different analysis-modeling problem.

In 1982, Azuma and Saito [6] studied rotor gust response using local momentum theory and concluded that unsteady aerodynamics are not a significant factor, that rotor blade bending effects are significant and attenuate the gust load factor as opposed to aircraft where structural flexibility amplifies response, and that rotor gust response is not sensitive to Lock number,

$$\gamma = acR^4/I.$$

The V/STOL aircraft, when compared to the helicopter, has relatively small aerodynamic forces during approach and hover. In general, the control of a V/STOL vehicle at slow speed is very dependent on the propulsion system.

Etkin [7] noted several important differences between conventional aircraft and STOL/VTOL vehicles as follows: STOL/VTOL aircraft fly steeper descent paths, the lower flight path speeds accentuate the flight path response to turbulence and shear, and nonstationary statistical analysis methods must be used.

REVIEW OF HELICOPTER--V/STOL TURBULENCE MODEL DEVELOPMENT

It is interesting to review the development of Helicopter--V/STOL turbulence models with special emphasis on wind and turbulence spatial shear and flight dynamics model turbulence--wind input modeling. Basically, statistical gust models and analysis methods are considered because of their applicability to precise flight vehicle response to a random environment. Many important studies are not mentioned in the following discussion and references are chosen to illustrate a few stops along the path of design method evolutionary development.

Summers [8] conducted a flight test experiment using an instrumented B-26 as a probe to measure gust power spectra for

$$u_g, v_g, w_g, \frac{\partial w_g}{\partial y}, \text{ and } \partial u_g/\partial y.$$

He formulated the measurement problem to include effects of spanwise horizontal and vertical gust effects on the aircraft. Gust velocities were defined relative to quasi-internal axes moving with CG mean motion. He assumed that

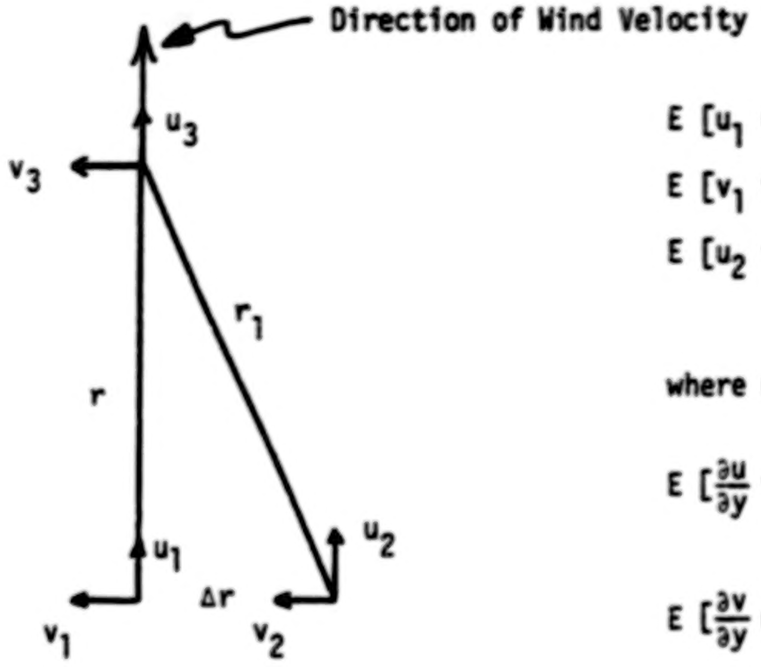
$$\frac{\partial w_g}{\partial y} = p_g \quad \text{and} \quad \frac{\partial u_g}{\partial y} = r_g$$

i.e., the assumption of small aircraft size relative to the gust eddy vortex size. The same basic formulation continues today.

In 1968, Skelton [9] conducted the first comprehensive V/STOL wind and gust model theoretical analysis and simulation. One objective of study was to recommend that TOLCAT experiments aimed at basic low-altitude V/STOL wind-turbulence model data acquisition. A few of the accomplishments of the study include: (a) development of a theoretical gust model forumulation for V/STOL aircraft in sideways or forward motion; and (b) a simple derivation of turbulence component (spatial) cross-correlations for isotropic turbulence. He derived the set of three-dimensional, spatial, non-zero cross-correlations which exist in isotropic turbulence due to wind shear as shown in Figure 1.

Skelton formulated TOLCAT experiment requirements for low-altitude wind and turbulence measurement, such as: (a) measurement of gust spectra at very low frequencies to define the wind-gust demarcation frequency; (b) measurement of joint probability densities for the mean wind amplitude, friction velocity, and gradient Richardson number as a function of altitude; and (c) seven more experiment definitions.

Elderkin [5] and others conducted perhaps most significant, classic V/STOL-helicopter-oriented low-altitude wind and turbulence model study. A few of the study accomplishments and limitations are as follows:


Direction of Wind Velocity
u_3
v_3
r_1
r
u_1
u_2
Δr
v_1
v_2

$$E\,[u_1\;u_3] = f(r)$$

$$E\,[v_1\;v_3] = g(r)$$

$$E\,[u_2\;v_3] = [(f(r_1) - g(r_1)]\,\frac{r\Delta r}{r_1{}^2}$$

$$\text{where } u_y = \frac{\partial u}{\partial y} = \frac{f(r) - g(r)}{r}$$

$$E\,[\frac{\partial u}{\partial y}\,v_3] = \frac{1}{2}\,\frac{\partial f(r)}{\partial r}$$

$$E\,[\frac{\partial v}{\partial y}\,u_3] = \text{non zero}$$

Figure 1. Non-Zero Cross-Correlations Which Exist in Isotropic Turbulence.

A. Individual and joint probability density functions were measured for all turbulence components. Power spectra were obtained by Fast Fourier Transform.

B. The spatial aspects of turbulence structure were studied along with the relationship between the temporal and spatial domains. Taylor's hypothesis was investigated and verified.

C. The theoretical analyses by Skelton [9] and Elderkin [5] are complete enough to furnish a sound basis for analysis of the data acquired.

D. Experimental data covered the lowest 200 feet of the atmosphere.

E. Taylor's hypothesis was verified for eddy sizes less than 10 times the height of the aircraft.

F. Spatial data may be translated to aircraft flight only for aircraft flying in the wind direction.

Schaeffer [10] reported on an FAA study of wind models for flight simulator certification of landing and approach guidance and control systems. The significant aspects of the study are as follows:

A. Developed a wind model in h <1000 feet.

B. Reviewed atmospheric turbulence modeling theory.

C. Transformed turbulence components from each axis to aircraft body axis.

D. Defined effective turbulence angular velocities in the same sense as Summers [8] and Skelton [9] to account for spatial wind gradients.

E. Proposed a wind-turbulence model for automatic landing certification.

All of the above wind and gust models basically utilize model mean wind characteristics and isotropic-homogeneous gust turbulence. A second approach to wind modeling evolved in parallel to the stationary gust models. NASA launch vehicle design for winds aloft and gust response utilized nonstationary statistical analysis methodology, synthesized deterministic wind profiles based on winds aloft statistics, and used Monte Carlo simulation of vehicle responses utilizing winds aloft data.

In 1967, Bailey, Palmer and Wheeler [11] synthesized a wind aloft model shaping filter for both wind and turbulence. Nonstationary shaping filter differential equation coefficients were derived with multiple linear regression techniques. The model was utilized to determine launch vehicle response characteristics by the nonstationary statistical adjoint method. This planar analysis is now well formulated in higher dimension utilizing a matrix formulation. The nonstationary statistical approach is perhaps the most applicable methodology for solution and simulation of the dynamic wind (wind shear).

problem. The above analysis followed the work of Bieber [12].

Tatum et al. [13] developed a nonrecursive turbulence model for simulation of space shuttle ascent trajectories. One-dimensional gusts and gust gradients are developed from three-dimensional von Karman spectra, integrated over the flight vehicle dimensions. Digital filter theory was utilized to develop a nonrecursive diecrete shaping filter for Monte Carlo turbulence velocity generation. This analysis method generated time series of both linear gust velocities and gust gradients (u_1, u_2, u_3)

$$\partial u_2/\partial x_1,\ \partial u_3/\partial x_1,\ \partial u_3/\partial x_2,\ \text{and}\ \partial u_1/\partial x_2$$

for tape storage and future playback. The resultant analysis methods utilized a different approach from that of Etkin [7], but both methods included first order effects of wind shear.

Smith and Lambert [14] developed a synthetic wind profile based on properties of the quadravariate normal probability distribution function for Kennedy Space Center winds aloft. The deterministic wind design profile was utilized to determine ascent loads for the space shuttle. The synthetic vector wind profile (SVWP) is formed as the distribution of wind shears which varies with the mean wind vector at a reference height, altitude, month, and launch site. The 99% conditional shears are used in the SVWP. The concept of synthetic wind profiles for design has been developed by NASA for the Apollo and Shuttle programs. The method by Smith provides some theoretical justification for the SVWP choice.

The preceding references on wind and gust modeling basically outline the necessary methodology to establish fundamental design wind and turbulence models for microburst type events. Model formats which may be postulated are as follows:

1. Synthetic microburst profile based on nonstationary statistical analysis of wind shear event data.

2. Nonstationary Statistical Model based on current data available.

The resultant model format could evolve based on a three-dimensional jet model or by brute-force statistical analysis of available microburst data.

Analysis techniques and methodology applicable to the microburst-type events seem to be well developed. Model development should be straightforward when an event data base is well developed. The basic data is probably available for hover turbulence model specification. However, further analytical method development is necessary to input the gust velocities realistically into the rotorcraft flight dynamics mathematical model.

During the preparation of this paper, three helicopter manufacturers were surveyed as to their wind and gust modeling design methodology. They typically used both discrete and continuous gust models for design and simulation. The primary deficiencies in industry practices today seem to be lack of a good hover turbulence model and inadequate design inputs for microburst-type wind events.

Two high-time helicopter instructor pilots were interviewed as to their perception of microburst-type dynamic wind events. They were aware of the problem and had seen U. S. Army and FAA material on the subject. Neither pilot had encountered a microburst event although both pilots agreed that on both takeoff and landing, under heavily loaded conditions, wind events with high shear could be a problem for helicopters.

CONCLUSIONS

In general, wind and turbulence modeling for helicopters and V/STOL rotorcraft is more complex than for conventional aircraft. The state-of-the-art for wind and turbulence model application to rotary-wing and V/STOL aircraft is not well developed and several notable gaps exist, such as lack of verified gust models for the hover case. Basic rotor blade turbulence response theory is currently evolving in the scientific literature for the general rotorcraft dynamic response case. Several conclusions that may be stated from this rather quick look at the rotorcraft--V/STOL dynamic wind and turbulence design problem are as follows:

1. Dynamic wind response of aircraft and rotorcraft in forward flight may be analyzed by similar techniques. Wind and turbulence models which suffice for aircraft analysis requirements will likely meet rotorcraft design requirements for high-speed forward flight.

2. Helicopter, rotary wind V/STOL, and propulsion-dominated V/STOL aircraft during transition and hover flight present a very different set of requirements on the wind model. Hover turbulence models can probably be formulated from existing data bases but much work remains for rotorcraft applications.

3. In general, modeling methodology and concepts have changed little over the past 30 years. Primarily, refinements have been added to wind and turbulence models conceived in the 1950's. Wind and turbulence spanwise and chordwise effects on the aircraft are well approximated by both historical and current modeling methodology.

4. Techniques developed by NASA for modeling launch vehicle wind aloft response seem directly applicable to the microburst phenomenon. Nonstationary statistical models present no major problems when used in conjunction with manned simulations. Modern digital technology simplifies generation of nonstationary wind and turbulence time series. Analysis of piloted simulator results for nonstationary events is more difficult.

5. The synthetic wind profile concept is a definite contender for both vehicle design (control system and structural) and piloted simulator training.

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ACCIDENT INVESTIGATION

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INTRODUCTION

I am certain that everyone shares the interest of the National Transportation Safety Board (NTSB) in reducing our accident investigation workload. The NTSB is not, in the classical sense, a user of wind shear data. We have no R&D capability, no simulators, and very little technical capability in our organization to do in-depth analyses. However, even before the JAWS Project began, we managed to develop some reasonably good wind shear models that have been used to improve pilot training programs by using some of the accident investigation data which came from flight recorders. Many people in the industry have helped us with this considerably. We were very happy to see the JAWS Project get under way so that we could improve upon that data base. We certainly join the rest of the aviation community in our desire to ensure that the data base is used to its maximum advantage to improve safety.

We are assured that wind shear has been around forever. However, we really didn't focus in on the wind shear problem until the early 1970's, although many accidents occurred before that time which were attributed to thunderstorm penetration and other types of weather phenomena (just different names for the wind shear environment). There may be a reason that wind shear has received more attention since the early 1970's. I think that with the advent of higher speed, higher wing-loaded aircraft, along with the better instrument capability of both the airplane and ground navigational aids, the chance of a wind shear encounter is much greater today than it was several years ago. We have more planes flying into poor weather. They are designed to do that; in addition, the airplane itself might be more critical to the wind shear encounter.

NTSB has attributed wind shear as a cause or contributing factor in 15 accidents involving transport-category airplanes since 1970. Nine of these were nonfatal; but the other six accounted for 440 lives. Five of the fatal accidents and seven of the non-fatal accidents involved encounters with convective downbursts or microbursts. Of other accidents, two which were non-fatal were encounters with a frontal system shear, and one which was fatal was the result of a terrain-induced wind shear.

The actions have stressed, first and foremost, the avoidance of wind shear encounters; and, secondly, the actions needed to help a pilot get through it if he encounters wind shear. I believe that one of the major objectives of this workshop is to address how the JAWS data can be used to develop models for the certification of aircraft systems and pilot training. We totally support these efforts, but feel that we must also address the need to learn how to use the data obtained from JAWS to improve forecasting and for development of real-time detection of the hazard threat. I think we also need to address the fact that even if and when we get optimum airport instrumentation, such as terminal microwave Doppler radar, we have a lot of work to determine how to introduce the data provided from that system into the pilot's decision-making loop. This is still a cause for very much concern. Even more importantly, how can we more effectively use the LLWSAS? Can we use the JAWS data to identify a hazards threat from the LLWSAS so that it can be communicated in a meaningful way to the pilot?

I cannot ignore the fact that it has been nine years since Eastern 66 in New York; and nearly two years now since the Pan Am accident in New Orleans. But today, given the same circumstances, I'm not sure that the same accident couldn't happen. Let's hope it doesn't. Keep in mind that despite the amount of progress we can claim during the last two years, I don't know that there have been any real, firm actions that could have changed the situation as it occurred in New Orleans in July of 1982.

We totally support the use of the JAWS data for developing practical models of the microburst for system certification purposes and training. We are aware, however, that more efforts need to be conducted to determine how complex or sophisticated these models have to be. I agree with many people who have indicated that they believe the FAA should take the lead here, but they need industry help. The FAA does have to stay very much a part of these efforts, and they must define the model so that everyone is working toward the same goal, at least in system certification.

At any rate, we already know the types of flight directors and autoflight logic which need to be developed and implemented in order to optimize the airplane's performance in the case of a wind shear or microburst encounter. We have had, for some time, sufficient knowledge of the general characteristics of the downburst and outflow to identify how the logic of the current systems needs to be changed. Even more importantly, we have to identify the systems that are presently in use, and will remain in use for several years to come, which do not incorporate the optimum logic in order to tell a pilot when he might have to disregard what he has learned in the past in order to take some rather strange evasive action. I know there are efforts under way to do this, but I'm not sure they are quite as systematic as we would like to see.

That brings me to the training aspect. We have a lot of concern from the point that I'm afraid we tend to place too much emphasis on simulator models in training. There is certainly a need to demonstrate to the pilot what happens to his airplane when encountering a microburst; but there is only so much time in which to do this, and only so many encounters can be demonstrated, and they are not all the same. The condition of the encounter during the approach on the ILS glidepath is not the same as the encounter during departure or takeoff. One encounter which interests me very much because it resulted in an accident is the Allegheny DC-9 in Philadelphia, where the airplane actually encountered the outflow of a microburst/downburst beyond the touchsown point along the runway. It was located at the departure end of the runway which the aircraft was approaching. In this particular case, the airplane was in trouble before it ever reached the center of the disturbance. The airspeed built up as a result of running into the outflow; the airspeed didn't bleed off, and the airplane didn't land. The pilot saw that he was long and fast over a wet runway, and he initiated a go-around which put him right in the middle of it.

We certainly need reasonable fidelity in the simulations. For example, we need to demonstrate what kind of control forces the pilot might be confronted with then he takes some of these radical actions. This probably reflects one of the biggest uses of the simulator. We also have to demonstrate the need to rapidly add thrust if the pilot is in a position where he has available thrust to add. Even though we get good academic models, we need to augment the simulator work to actually teach the pilot the fundamentals of what is happening to his airplane during wind shear encounters to prepare him in any phase of flight.

I certainly hope that the large emphasis on the microburst and its phenomenon as a result of the JAWS Project does not lead us to ignore the frontal system shear, which is probably not as dangerous from the significance of the winds, but has caused accidents. The Iberia DC-10 accident in Boston in 1972, although non-fatal, could very easily have resulted in the loss of a wide-bodied airplane full of people. We need to develop a syllabus which treats both the microburst and the frontal system shear. We need to tell pilots how to recognize when either condition might exist and how to avoid it. It is evident to us that there is a need to eliminate bad information which is currently in the training syllabus.

The NTSB is currently investigating two accidents. One is the Flying Tigers DC-8 which landed at Navy Norfolk in Octover of 1983; the other is the SAS DC-10 which landed at JFK in February 1984. It may not be possible to point to wind shear as a primary cause of either of these accidents; however, in both cases, the pilot was aware that the possibility of wind shear existed. A wind shear did, in fact, exist in the SAS case, but the pilots apparently misunderstood what they should have done for that type of wind shear. In both cases, wind shear to the pilots meant, "Hey, I better add enough speed to compensate in case I run into something on this approach." As it turned out, they added speed but didn't bleed it off; in both cases, the airplanes landed long and fast. In one case, it was on a flooded runway that resulted in a hydroplaning aspect; in the other, there was just too little runway left in which to stop.

In summary, I would like to note that someone has to take the lead to ensure the continuity of a systematic program to coordinate all the activities being conducted on the wind shear problem. However, I feel that the FAA will need the continuing support and input from the R&D organization; i.e., academia, industry, and airframe and systems manufacturers. Furthermore, many recommendations have been made by both the Safety Board and the National Academy. It is important to note that after a National Academy study is completed and their report is released, that report remains on a bookshelf with no one around to pull it off and relate what has happened. That is one reason we are so encouraged by the formation of this ad hoc committee. Although it may be beyond the scope of their charter, I believe it would be well to consider keeping this committee intact to convene periodically to discuss what actions are being taken to implement the Academy recommendations, and to exchange information relative to what is happening in industry.

I also feel that this ad hoc committee could be very useful in, perhaps, communicating the needs to the carriers: i.e., to define the hazard threat;

to determine the communication means to alert the pilot of a possible wind shear condition (or a real-time detection of one), encouraging him to make a decision to not penetrate it on that basis; to improve the on-board systems, both the flight director and automatic flight control systems (and we certainly subscribe to the thought that an automatic flight control might be an answer to the problem); and to continue to emphasize the improvement of training.

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AIRBORNE DOPPLER RADAR FOR WIND SHEAR DETECTION

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INTRODUCTION

There has been extensive discussion concerning the use of ground-based Doppler radars for the detection and measurement of microburst features and the mapping of associated wind shears. In this paper, I shall address recent and planned research at the Langley Research Center into technology and techniques useful for the future development of airborne Doppler weather radar systems for both turbulence and wind shear detection. Such systems, if successfully developed, would represent a marked increase in performance over airborne weather radars currently available. A principal difficulty in extending to airborne radars the capabilities of current ground-based Doppler radars can be seen in the following way.

Consider an airborne radar observing a resolution cell ahead of the aircraft. The transverse dimensions of the cell are determined by the width of the antenna main lobe and the longitudinal dimension by "range gating" the received signal. Within this cell, a population of water droplets scatters power back to the radar, and the magnitude of this power is related to the rainfall rate or "dBZ" level of the cell. Until recently this power level was the only measurement available to airborne weather radars. Additionally, the frequency of the radiation scattered by each droplet is altered from that of the transmitted signal by the relative radial velocity between the droplet and the radar. A Doppler radar is sensitive to these frequency shifts and is, thus, able to measure radial velocity features of the cell. The horizontal velocities of the droplets tend to equilibrate with the local wind field, so that the Doppler spectrum of the received radar signal is a measure of the radial component of the horizontal turbulence spectrum, appropriately averaged over the cell. The mean value of this spectrum is then related to the mean wind velocity in the cell. If this mean velocity is measured cell-to-cell, then the large-scale wind variation, or wind shear, can be measured along with the turbulence within each cell.

Because of the rapid motion of the aircraft, the absolute values of these mean radial relative velocities are much larger than those usually encountered with ground-based radars. Further, the resulting measured velocities vary widely with antenna scan angle. These factors combine to make very difficult the measurement of mean wind velocity with an airborne radar. In fact, the newest generation of commercially available airborne Doppler radars makes no attempt to do so. In the next section I will describe some past experiments by the Langley Research Center with a radar developed in-house for the purpose of making both turbulence and mean velocity measurements.

PAST EXPERIMENT PROGRAM

In the summer of 1982, experiments were performed involving two aircraft and a ground-based Doppler radar in the environments of the NASA Wallops Flight Center. One of the aircraft was the Langley F-106 thunderstorm penetrator, which is involved in the aviation Storm Hazards Program under the leadership of Norman Crabill. The F-106 contained instrumentation for measuring the complete turbulent wind field and resulting aircraft accelerations within a thunderstorm. The second aircraft was the NASA Wallops "Skyvan" in which was installed the Langley airborne pulsed-Doppler research radar system. The objective of the Skyvan was to position itself outside of a thunderstorm such that its on-board radar could observe the storm environment in which the F-106 was simultaneously flying. The ground-based Wallops "Spandar" radar was provided with separate sets of equipment by both Langley and the Air Force Geophysics Laboratory for the collection of Doppler radar "truth" data. Figure 1 is a sketch of the experimental configuration.

As can be seen, the two aircraft would position themselves such that both would fly along a radial line to the Spandar radar. The Skyvan radar would view rearward along its line-of-flight while the F-106 would make passes in both radial directions through the thunderstorm. Data were collected for several thunderstorms on a smaller number of thunderstorm days. In order to measure successfully the mean wind velocities along the line-of-flight, the Skyvan research radar utilized a special airspeed compensation scheme. This compensation involved a computer-aided feedback loop which was used to track the relative velocity between the Skyvan and a resolution cell under observation and to control an oscillator in the radar so as to translate the Doppler spectrum into the first "Nyquist interval". In this way, all of the Doppler information, including both mean and turbulent velocities relative to the Skyvan, could be recorded unambiguously. It should be emphasized that this scheme required no real-time input of air or ground speed to the radar.

Figure 2 shows a sample of data collected by the Skyvan radar. Plotted is mean radial velocity versus distance from the Skyvan. Shown in the lower right corner are mean velocity values for successive range bins for two adjacent pointing directions. The curves show gradients in the mean wind, i.e., shear, both along the transverse to the line-of-sight of the radar. The measured values of the shear are typical of those known to occur in representative thunderstorms. What is important here is that these curves illustrate that radar techniques of the kind used can, in fact, measure wind shear aloft despite the rapid aircraft motion. Measurement of hazardous wind shear near the ground, however, is a much more difficult matter and will require even more sophisticated radar techniques. The next section will offer some considerations relative to the detection of microbursts at very low altitudes with airborne radar.

LOW-ALTITUDE WIND SHEAR DETECTION

Several new aspects appear for the airborne weather radar when applied to operations near the ground. Some of these pertain to:

- Vertical resolution and its effects on microburst "signature" recognition and shear-induced spectral width;

- Ground clutter contamination in both main and side lobes.

Consider an aircraft on its final approach at a distance of 10 km from touchdown and descending along a 3° glide slope. Its altitude at that point is about 500 meters. Since the antenna beamwidth of a currently typical airborne radar is also about 3°, the vertical extent of the radar resolution cell at the point of touchdown is also 500 meters. Now the predominant outflow

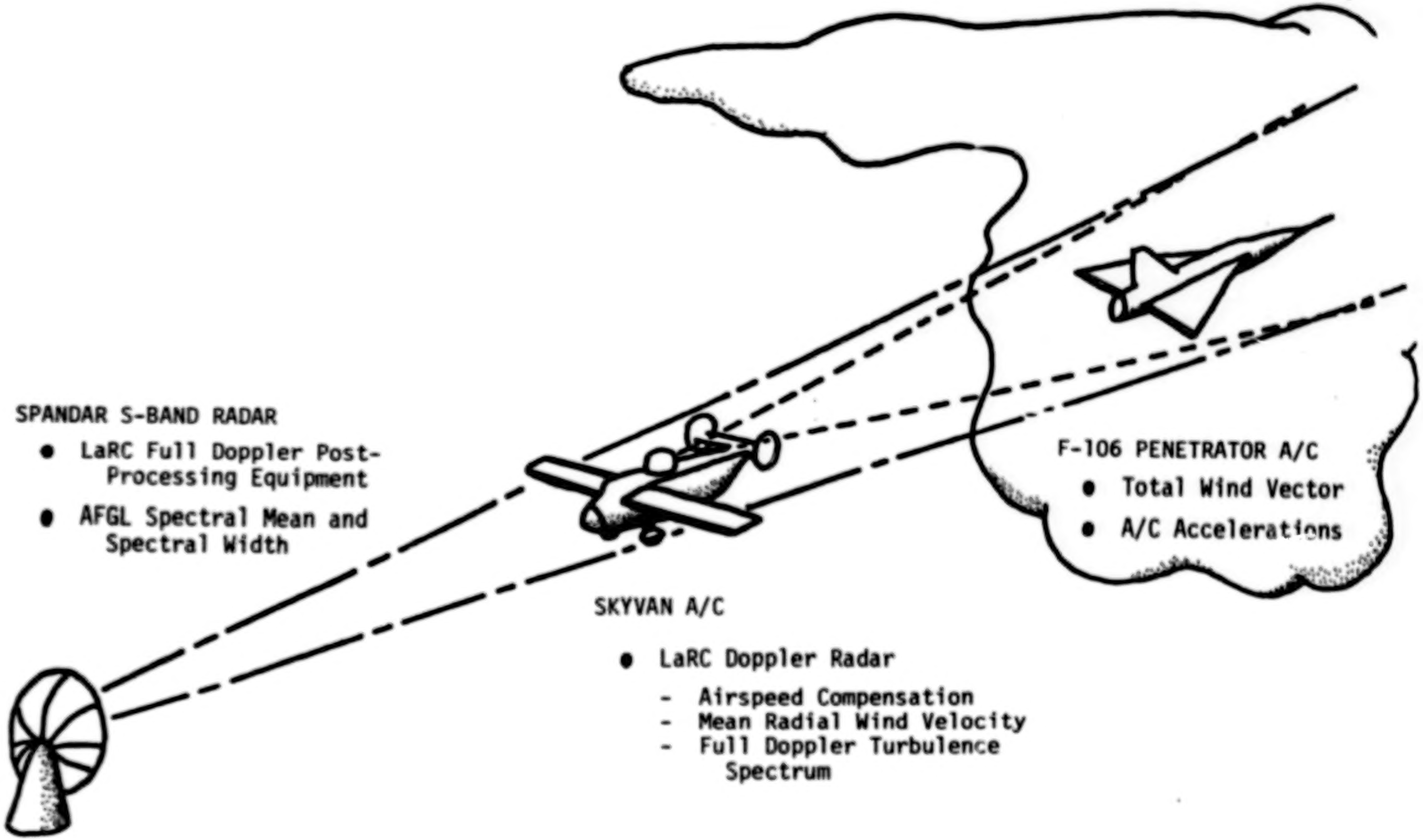
SPANDAR S-BAND RADAR
• LaRC Full Doppler Post-Processing Equipment
• AFGL Spectral Mean and Spectral Width
SKYVAN A/C
• LaRC Doppler Radar
- Airspeed Compensation
- Mean Radial Wind Velocity
- Full Doppler Turbulence Spectrum
F-106 PENETRATOR A/C
• Total Wind Vector
• A/C Accelerations

Figure 1. Doppler Radar Turbulence - Wind Shear Experiments (Summer 1982).

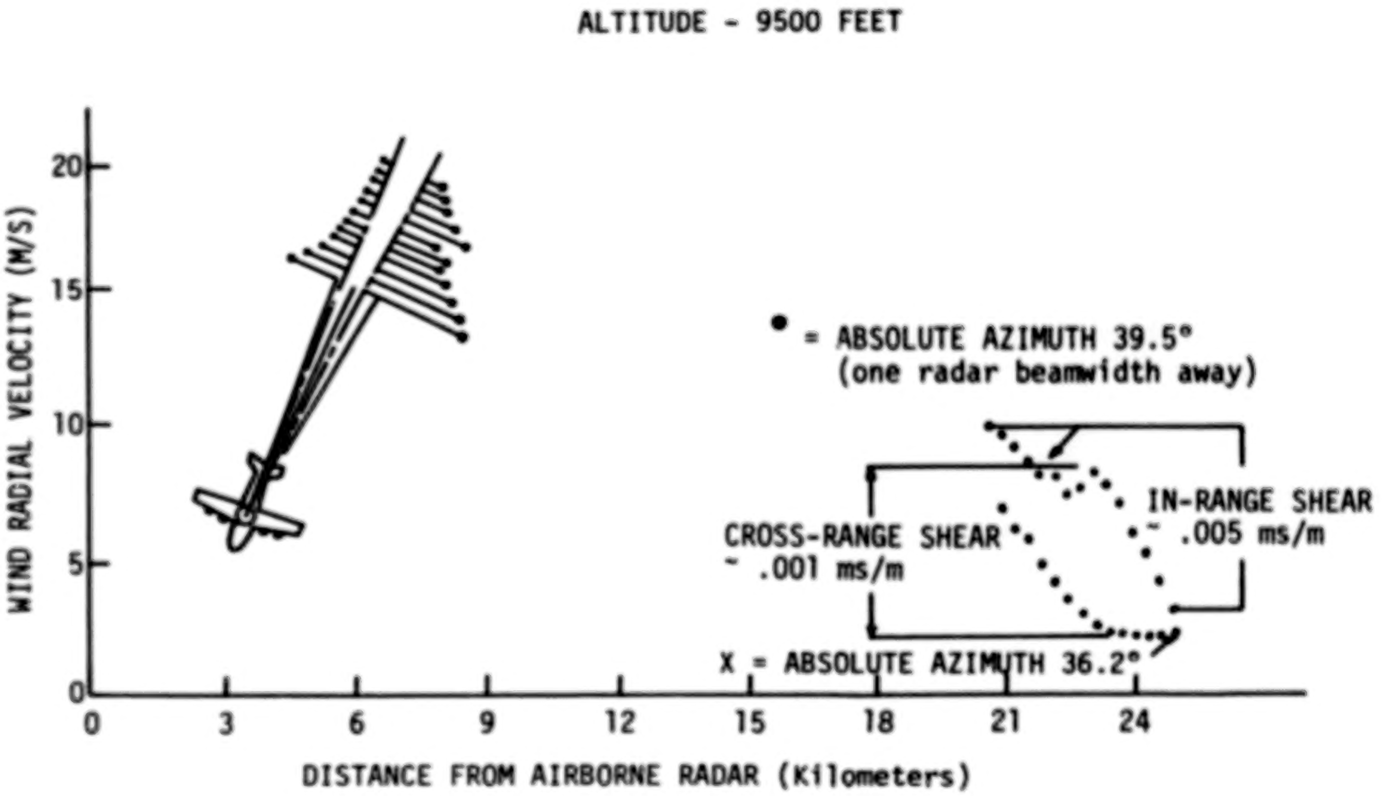

Figure 2. Wind radial velocities measured with airborne radar in thunderstorm of July 28, 1982.

from a microburst occurs below 1 km, so that two vertically contiguous resolution cells would cover the outflow region. To do this effectively, however, the radar antenna would need automatic scanning in the vertical direction. Present airborne weather radars do not have this feature, but a more serious problem with this vertical resolution cell size is the velocity spectral width that must be dealt with.

It seems that in the passage of a typical thunderstorm, there is a 50/50 chance that the vertical shear in the horizontal wind passing the tower will exceed 25 meters/second over the height of the tower (500 m). Even in the absence of any actual turbulence, this amount of shear would produce an effective turbulent spectral width that is wider than that which can be handled by the latest commercial X-band airborne Doppler radars. This spectral width coupled with the large horizontal gradients in the microburst outflow would require dramatic increases in the transmitted pulse repetition frequency (PRF) of a conventional pulsed-Doppler radar. Increasing the PRF can, in turn, cause problems with "second-time echoes", which are signal returns that lie beyond the ranging capability of the radar and appear to the system to lie much closer than their true positions.

Perhaps one of the more serious potential problems facing the airborne wind-shear radar is the contamination produced by spurious returns from portions of the ground contained in the antenna side lobes. The relative velocity of these signal returns ranges from zero for signals received abeam the aircraft up to the ground speed for signals directly ahead. If these side lobe clutter signals are sufficiently strong, then no practical value for the PRF could be achieved, and more complex modulation schemes would be needed. It is, of course, not clear to what extent the above conclusion from tower data is representative of microburst conditions or how difficult the side lobe clutter will really prove to be. However, if analysis of JAWS and similar data supports the need to deal with such shear levels, then substantial changes in airborne radar characteristics may be required. Since a recent joint study by a committee representing the National Research Council [1] has advocated research into the use of airborne Doppler radars for ameliorating the wind shear problem, there is renewed interest in structuring an appropriate research program to define actual conditions and to support development of those new radars.

PROPOSED AIRBORNE RADAR RESEARCH PROGRAM

In order to answer some of these questions, a new research program has been proposed by the Langley Research Center for joint support by NASA and the FAA. The program has among its goals the following items related to the physics of the measurement and the interpretation of the associated hazard:

- Extraction of the raindrop "clutter-like" signal from the (moving) ground clutter;

- Scanning techniques for measurement of the microburst "signature";

- Determination of the utility of frequencies above X-band;

- Development of hazard recognition and alarm algorithms from the measured signatures;
- Development of practical methods of obtaining high-quality field data with reasonable aircraft flight time.

A first job is to determine what existing instrumentation can be of value to the new program. The present status of airborne Doppler weather radars can be represented by the characteristics of three radar systems. These are a) the NOAA-P3 X-band airborne radar and its improved version presently being developed by NCAR; b) the NASA Langley airborne Doppler research radar; and c) the newest commercially available airborne turbulence radars, a representative of which is the Collins WXR-700 model.

The NOAA-NCAR Doppler radar has been successfully used in a variety of atmospheric research programs. Its chief limitation for purposes of developing the desired new wind shear radars is that its antenna is mounted in a tail-sting radome and is constrained to view perpendicularly to the line-of-flight. Accordingly, it has no need, and no capacity, for elaborate airspeed compensation functions. It does have a relatively narrow antenna beamwidth, but this is obtained from an antenna that is too large for general application in the nose radomes of most aircraft.

The NASA Langley radar has been discussed earlier. Its salient characteristics are as follows:

- Frequency: 13.9 GHz
- Pulse rep. freq.: 3000/sec
- Pulse length: 2 microsec
- Antenna beamwidth: 3.3 deg
- Trans. power: 2 kW peak
- Unambiguous range: 50 km
- Unambiguous velocity: ± 16.2 m/s about compensated airspeed
- Res. cell length: 300 m

Major limitations of the radar for the low-level wind shear research application relate to its inflexible pulse modulation parameters and antenna characteristics.

Representative of the new commercial airborne radars is the Collins WXR-700, which has the following characteristics:

- Frequency: X-band
- Pulse rep. freq.: 1440/sec
- Pulse length: 6 microsec
- Antenna beamwidth: 3.2 deg
- Trans. power: 125 W peak
- Unambiguous range: 104 km
- Unambiguous velocity ± 11.4 m/s (spectral width only)
- Res. cell length: 900 m

The large resolution cell size (approximately 1/3 of a runway length) and the rather small unambiguous velocity interval of such a radar may be inadequate for the needed research program, although a modified version of it could well be useful in the upward-looking mode while stationary on the ground. It is evident from the above that a new airborne radar research instrument is required for the new program.

The proposed radar system will be modularly constructed such that different transmitters and modulating schemes may be used with common intermediate frequency and "back-end" electronics. It is planned to have dual receiver channels so that both direct and cross-polarized signals can be studied; thus, dual receiving antenna positions can be used. To overcome the difficulty of gathering a sufficient quantity of airborne data to study both microburst and ground-clutter features, it is proposed that data be collected in two separate forms and merged later.

First, a suitable ground-based radar would be configured such that it truly represented airborne radar characteristics. This radar would be deployed as part of a joint field program for the study of airport weather such as that currently being conducted by the FAA in Memphis, Tennessee. In this mode, the radar would obtain full time-series data on weather targets of opportunity in the presence of "truth" data provided by other sensors. This radar data would have the effects of (non-moving) ground clutter removed by conventional means. Later, the completed airborne research radar would fly airport passes in wet weather but not necessarily in microburst conditions. The primary purpose of these flights would be to obtain full time-series data for the moving ground clutter. After suitable adjustment of the "noise-levels" of the two sets of data, airborne and ground, the time series would be combined to represent a composite signal having both microburst data and realistic airborne ground clutter. Upon this "truth data" candidate algorithms and techniques for true wind shear signature extraction could be verified. Promising approaches could then be implemented in hardware for future flight testing. The research program described would, thus, significantly involve analytical and computer studies as well as radar hardware. To carry out such a program, it is evident that expeditious use must be made of all data presently available, such as that obtained in JAWS.

WIND-FIELD AND RAINFALL MODELS FROM JAWS

Should the program discussed receive appropriate funding in the fall of 1984, it is proposed immediately to begin cooperative efforts with interested JAWS investigators. A workshop will be held at Langley involving them along with representatives of the weather radar community to help fashion the wind shear program in the most effective way. Interaction with JAWS researchers would seek to define wind-field models to denote what a single, moving radar might see in approaching an airport. These wind-fields, along with realistic rainfall rate models, would serve as the initial basis for developing expected radar signatures in the early analytical work. Techniques developed in this early work could then be tested against a larger body of data as the JAWS data reduction continued. Although the final test of the wind shear radar must come in the air, data such as that from JAWS will be of inestimable worth in designing it and proving its technology.

REFERENCE

1. NRC-NAS Committee on Low-Altitude Wind Shear and its Hazard to Aviation: "Low-Altitude Wind Shear and Its Hazard to Aviation;" National Academy Press, Washington, DC, 1983.

QUESTION:

Previously, there was some discussion about airborne radars being ineffective when no moisture is present in the air. However, it was also stated that even though no moisture is present, there are generally a lot of bugs, and you can measure the velocity of the insects. Apparently this was based on experience in the JAWS data experiment. Could you comment on whether this has been your experience?

RESPONSE:

Insects of all kinds have been seen on ground-based radars for years. It is now thought that they account for a large number of the angels or false echoes that were seen and were regarded as completely unexplainable. On our airborne radar I have never seen anything which I would associate with an insect; but I haven't looked for it, either. I would think, however, that the insect population would be sufficiently sparse to have very many of them in a resolution cell. If you have two of them, for example, those signals beat together and result in a highly fluctuating target with only two samples in it. To get a good stable target there needs to be a large number of drops (certainly over 10, and maybe even 100) in a resolution cell. Even though you may see them, they are not complete tracers of what is going on in that cell; certainly not in the tracer of the turbulence.

QUESTION:

The work done in Severe Storms Lab and at Boulder seems to contradict that. There are two sources of reflectivity on ground-based radars which are showing up very heavily in the optically clear air. These are refractive index gradients and insects. Some work done particularly at the Severe Storms Lab shows that the insect population in convective boundary layer is extremely high. They represent a substantial reflectivity source. Combined with refracted index gradients, a very sensitive ground-based radar, obviously with a large antenna, is quite capable of seeing all kinds of action in the convective boundary layer. I think the issue here is whether an airborne system can be designed with sufficient sensitivity to get targets in the optically clear air. That, to me, is the nature of the question. There is no doubt that there is a lot of reflectivity in a summer-type convective boundary layer. Every ground-based Doppler radar is seeing optically clear air, and getting good velocity measurements in it.

RESPONSE:

Yes, I have done some work in looking at the optically clear air with a 60 ft. dish antenna at Wallops. At S-Band, you have to work at it a little in order to see things at very high altitude; therefore, it is not the kind of thing that reasonable airborne radar will be able to do.

QUESTION:

Again, this only works on a ground-based radar in the boundary layer where there are bugs and, also, refracted index gradients. Above the boundary layer, it is zero. There is nothing there; but with the microburst signature, we're talking about convective boundary layer.

RESPONSE:

That is an interesting point which certainly deserves to be looked at.

QUESTION:

Do you see a reasonable antenna size in the future, say after 1987?

RESPONSE:

Yes, if you're talking about larger airplanes. I think we can talk about 3 ft. or so, reasonably, for something that might be put in the radome as an upper bound. If we want to look at smaller airplanes, of course, that commercial sizes. Twenty-four inches at X-Band gives you about 3°; thirty inches would be a little less than that.

QUESTION:

Would you discuss the use of airborne Doppler radar for the cruise mode of flight? You would size it so that it would take care of the wind shear environment at low altitude. How about the cruise conditions at a higher altitude in terms of still being able to get the reflectivity turbulence and winds?

RESPONSE:

I mentioned the possibility of the ultimate radar being a higher frequency; in fact, we want to do some experiments up to 35 GHz. Since we are lower to the ground and don't have to see as far, we could probably get away with lower power levels at that higher frequency than we would for the en route problem. So, it could well be that the final radar would be a dual-frequency radar where everything from the IF on down would be common to both of them; but we would switch between two transmitters. There are any number of things that might accommodate that. Certainly, to make it useful and acciptable, these functions must be included in the weather radar. I would like to add that general purpose radar (which we are talking about building) obviously has more performance potential than we're ever going to have in any real radar that's useful. That we have to do is abstract from all these variables the things which we really can use to identify the signature, and use only those in the operational version.

QUESTION:

I realize that this is limiting, but if we are specifically interested in detecting microbursts when we are at low altitude, rather than looking, necessarily, at an elaborate horizontal signature in front of the aircraft, the really strong identifying feature is the vertical shaft. It is conceivable that this radar, instead of looking in front of the airplane, should be looking upward, for example, at 45° when it's in the landing mode. This would solve the ground clutter problem and also be specifically designed to look for that vertical shaft. That, in combination with the fact that you have suddenly nosed up because of a sudden head wind, would be sort of a dual confirmation that there is a microburst.

RESPONSE:

By the time you have nosed up, you are already in a regime where your radar has not done you much good. The advantage of radar is to be able to see ahead of the airplane. Now, whether we could identify this feature looking up at 45° would have to be answered by something like the JAWS data. If that feature shows up, then by all means, we would include that vertical scan.

IMPROMPTU PRESENTATIONS
ON
UNITED AIRLINES INCIDENT

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N87-25287

UNITED AIRLINES WIND SHEAR INCIDENT

OF MAY 31, 1984

DAVID A. SIMMON: UNITED AIRLINES

The information contained in this report of a wind shear incident occurring at Stapleton Airport, Denver, CO, is preliminary in nature. United Flight 633 from Denver to Phoenix departed Denver sometime in the middle of the afternoon. The aircraft was a stretched 727 (aircraft 7647) with JT8D-7 engines. It had the old type flight data recorder which doesn't have quite the resolution that we would all like. The gross weight of the flight was 146,200 lb, which was about 7,000 lb under the maximum allowable takeoff weight. The V1, V2, V2 speeds for the 5° flap takeoff were 139, 139, and 150. They were using runway 35 left, which is 11,500 ft. in length, and by the way, is the same runway where the Continental accident occurred a few years ago.

The weather was high overcast, 83° with a dew point of 38°. The winds were quite variable, we understand, and very squirrely. At the time of takeoff, the winds were 280° at 20 and there was some blowing dust in the area. Denver tower had stopped departures 20 to 40 minutes before this incident, due to wind changes which had gone from north to south and then to west, where it stabilized at about 20 kts. The third aircraft in front of 663 reported a 20 kt airspeed loss on takeoff. The next two airplanes took off and apparently had no indication of wind shear.

Prior to takeoff, the crew had discussed the possibility of wind shear and had decided to use max-rated thrust, although they were 7,000 lb under the maximum allowable gross weight and could have used derated thrust. I think the use of max-rated thrust is important and will turn out to be significant in this incident. At about 120 kts, the crew noticed that the airspeed acceleration slowed or stopped. This airspeed "hang-up" will be important as we analyze this whole incident since it is a very good indication of wind shear. The airspeed increased to VR and the rotation was begun. Apparently the shear hit about that time, or let's say, the second shear, since the first one occurred when they noticed the airspeed aberration on the runway. The Second-Officer of Flight 663 was an instructor and had also been through United's new test program in wind shear. At sometime during rotation, the speed started to decrease. The Second Officer observed the speed decrease and called out a loss of about 20 kts. He then continued making callouts and said something like, "Keep the nose up," or "Keep up the nose," or "Backpressure." The callouts related to the training he received in our new test program. He then went to the vertical speed and called out, "Vertical speed 0, vertical speed 0, vertical speed 0," and about that time, saw the vertical speed jump to over 1,000 fpm, the airspeed increased above 160 kts, and they were out of it.

The crew didn't realize that they had contacted the ILS antennas which were 1,000 ft north of runway 35 left. I heard from the NTSB here today that there was a tire mark about 8 ft above the platform. Also a pipe or antenna, which was about 14 ft above the ground, ended up in the right side of the aircraft by

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the cargo door. It tore a hole in the airplane approximately 6" wide and 40" long. There was also a small hole and a scrape of about the same length on the left side of the aircraft. The flight attendant made a statement to the effect that she felt a bump, which would not be abnormal since she is sitting on the aft jump seat near the tail skid, which occasionally contacts the runway. After the crew started to climb out, they found they could not pressurize the aircraft; at that time, they elected to come back and land. They didn't know, until after they were back at the gate, the nature of the problem. By the way, there was no indication of stick shaker. The Second Officer thought the pitch attitude was around 12°. This is obviously all very preliminary information.

QUESTION:

What was the distance to lift off?

RESPONSE:

I can only give you some estimates. Runway 35L is 11,500 ft long. Since 663 was nearly runway limited, they would have been rotating about 3,000 to 4,000 ft from the end of the runway before considering the wind shear. The effect of the tail wind shear would be to move the aircraft closer to the end of the runway, but I can't tell you how much. It will be interesting to ask the Captain and First Officer about their perception. They obviously must have been pretty close to the end of the runway, since they ended up about 14 to 16 ft above the ground when they were 1,000 ft beyond the runway.

QUESTION:

Would you please outline the United Airlines training program?

RESPONSE:

Our current emphasis on wind shear training began as a result of a wind shear encounter in Chicago last year. The Boeing Company has been very helpful in analyzing the data and supplying us with technical information. We have been experimenting in our simulator for about three months with two of their wind shear models and one of ours. We are absolutely convinced that hands-on training is necessary to teach our crews how to recover from inadvertent wind shear encounters.

Again, we are not trying to teach our crews to fly through wind shears. Our number one line of defense has been and will always be to try to avoid this phenomenon. We recognize, however, that in situations like this, when the wind shear is not clear or obvious, our crews must be trained to recover from accidental encounters.

One of the more important items in "hands-on" training is stick force. An aircraft on takeoff is trimmed for V2+10 speed and if 20-30 kts are lost due to wind shear, considerable stick force will be required to keep the nose up. A rough rule of thumb is that a pound of stick force is needed for every knot under trim airspeed. Twenty to thirty pounds of stick force may, therefore, be needed during shears at the very time the pilot would normally be relaxing control wheel pressure as he approaches target pitch altitude. In the case of 663, the pilot probably had to deal with constantly increasing stick force as the airspeed was decreasing, which is different from his normal learned behavior.

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UNITED AIRLINES WIND SHEAR INCIDENT

OF MAY 31, 1984

JOHN MCCARTHY: NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

The NCAR Doppler was operating yesterday afternoon for another experiment and is located about 20 km straight north of Runway 35. It was doing 360° scans throughout the area and identified at 1330 a divergent outflow, or microburst, that passed just south of the VORTAC located approximately off the left side of Runway 35 left. The divergent center passed just on the west side of the runway. It moved very slowly and pulsed. It was very strong at 1330, decreased in intensity to about 1343, then increased rapidly in intensity at 1347, then at 1353 was no longer apparent. There was a small-scale microburst, essentially, with a single Doppler radar showing flow to the south and to the north.

The NCAR Doppler radar confirmed that there was a microburst center of divergence. The maximum reflectivity observed was 25 dbZ. It was a classical, high-based, non-thunderstorm virga case. Virga was observed throughout the area. The King-Air from NCAR was in flight at the time, doing soundings about 25 km north of the airport at the time of this incident. Therefore, we have a thermodynamic sounding and wind sounding at the time of the incident.

This is a relatively weak microburst case, however, and is near the bottom threshold of events that we looked at in JAWS; however, there are some difficulties with the information. It is considered a non-exciting borderline case. The radar was looking straight down the runway, so we have the head wind/tail wind component that is pertinent to the runway. The radar has been sited--not for Stapleton, but for another experiment located at the BAO tower north of Denver--and there is a blocking hill. So, the lowest elevation angle we have is 7/10 of a degree. Therefore, the winds that we see, and what we are reporting here, are no lower than 500 meters above the ground, so that the lowest flow is not seen by the Doppler. That is one reason it may be stronger than what we saw on the radar at the time.

A couple of things are important here. (1) There was a very strong convergence aloft at about 20,000 feet. There are some aloft signatures that were quite apparent in the case. (2) Another Fernando Caracena, who is working with us on JAWS very closely, does a daily microburst forecast. Yesterday morning, he predicted a high probability of microburst in Denver based on the 12Z sounding yesterday morning. It was a classical microburst case in terms of sounding, which means that three conditions were present: (a) there was mid-level moisture around 500 millibars; (b) there was a dry adiabatic lapse rate below the cloud base, below this mid-level moisture; and (c) it was very dry, as indicated by the temperature dewpoint difference. So, it met all the classical cases that we are developing as microburst forecast tools when conditions are ripe for microbursts. Extensive virga were reported in the area at the time this occurred. We know nothing about the LLWSAS at this time.

COMMITTEE
WORKING SESSION
REPORTS

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INTRODUCTION

The point that came out most strongly in this group's discussions was the need for a standardized wind shear microburst model derived from JAWS data analysis. The model should include mean velocity, reflectivity (or precipitation content), a broad range of values from what would be the average standard microburst to the one or two sigma distributions of wind speeds, skewness, asymmetries, vertical versus horizontal. A number of questions have been raised about how microbursts vary. It has been requested that turbulence be included. The model must be scientifically and/or engineering oriented and be representative of the JAWS data set; and the final product, not necessarily an NCAR product, must be applicable to many research and development simulations, a variety of training simulators, different phase simulators, and different aircraft-type simulations. It is clear that this model should also be available for use in other ways, such as development of detection systems, airborne instrumentation, low-level wind shear alert systems, terminal Doppler, and airborne Doppler. In other words, this generic engineering model should fit a much broader use than simply simulation.

.It also came out in the committee discussions that there is still a need for the detailed data set. The August 5 data set with reflectivity added was specifically requested as well as additional data sets which we would use to get to the generic model, or the generalized model. With regard to turbulence, it is clear that the desire to add turbulence to the data set is high. It is considered as a priority second to velocity and reflectivity. It was clear in the discussions that it should follow the proposed scenario of scaling turbulence in some algorithm using second moment data from the JAWS data set. Also, a point was raised to very carefully scale, or define the scale, of turbulence versus wind shear.

Another very important issue raised regarded JAWS data representation. That is, how well are the results from microbursts transferred to other climatological and geographical areas, i.e., can they be?

There was a substantial discussion in this and other groups concerning the vertical resolution of the JAWS data set. It was felt by some that the surface to approximately 750 meters, in terms of the grid size, was quite coarse for certain needs.

Another issue was the desire to be able to amplify or deamplify the JAWS data set. Given an actual data, such as August 5, can you increase or decrease the gain and still maintain reaiity? This is an issue which we feel should be addressed. Of course, in the derivation of the generic model, these kinds of issues are already implied.

IMPLEMENTATION ISSUES
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With regard to implementation initatives, the committee asked whether the current techniques are adequate. A convincing argument was made either for or against that notion; people do the best they can with what they have to work with. The opportunity afforded by the JAWS data base has allowed us now to do some things that we couldn't do in the past. We asked whether wind gradient information was needed. With regard to the quasi-steady aerodynamics and wind shear rotational components, the point is that a careful analysis of the aerodynamic effects is required to assess the impact of the span and streamwise gradients, which is vehicle specific.

The implementation is going to depend on how you start with your baseline simulator with regard to the aerodynamic representation. That is, adding wind shear effects to a lump parameter model is one thing we are doing. However, if distributed lift effects are important, add them. Nevertheless, in order to determine if they are important, you must model the effects that use gradient information.

These effects may impact more than the trajectory of the mass center; they may very well affect how the pilot perceives the simulator device and his attendant workload. Models that incorporate these effects may give the pilot a 5 or 6 degree of freedom control task as opposed to simply longitudinal power management performance response. It was suggested that the way the gradient effects are currently being handled in our simulator may not be a worst case analysis, and I tend to agree with this.

Simulator builders, as well as users, stated a strong interest in and need for guidelines. They want the gradient effects to be quantified. Early development and analysis should be conducted on R&D simulators where the computational complexity question is a non-issue. Work should continue on the effects and importance of gradient terms, but it should be loosely coupled with the JAWS effort.

With respect to wind shear models in the context of aviation, we have identified three significant activities: 1) systems design evaluation and certification; 2) flight crew training; and 3) R&D uses. Why do we want a new wind model? There is an overwhelming consensus that a technical standard is needed, as distinct from any notion of a regulatory standard. What is it that we want based on what we have talked about and heard in the last few days? We want a three-dimensional wind shear model of simple construct, but representative of the JAWS characteristics. The fact that it must be of simple construct does not necessarily mean the model is simple in utilization. A cadre of other wind shear phenomena needs to be added. We certainly do not want to throw away the best of the past and focus on microbursts only, but we want gust front phenomena, other frontal situations, seabreeze, perhaps even some mountain wave, and there are others that could be added. We desire inherent flexibility; that is, we should be able to move the wind shear domain around and locate critical scales of motion relative to significant points on the runway. We would like to have flexibility in establishing asymmetries in the model. A significant point is that the key model parameters should be based on the statistical analysis of the JAWS data. We still see this as a deterministic model, but based on statistical knowledge to set the ranges of severity and other key parameters.

The dimensions of the wind shear domain should be of minimal extent based on capturing the significant performance impact on airplanes. We may not need a domain of 14 km by 14 km with altitude ranges to 2,00
interesting cases where the training simulator people are implementing the entire numerical data base with arguments of achieving realism. Both CAE and Singer/ Link are implementing the volumetric data base, and one other company has also suggested that they are going to implement the entire volume data set.

A model will require reliable relationships between flow velocities, outflow, and downflow. These are keys issues. Exceedance probability analysis needs to be conducted. The FAA people posed the desire for a qualitative severity index, and we debated whether or not that index should be aircraft related or meteorological-parameter related. We tended to agree that it ought to be related to meteorology. What is severe for one airplane may not be severe for another.

The level of fidelity should be such that the inherent cues are consistent with the need for studying alerting and warning problems, recovery techniques, and avoidance. We may not know all the details necessary to state what fidelity means, but that needs to be studied.

Other specific enhancements may include turbulence and radar reflectivity to support things like color weather radars that are proliferating in training devices. From the point of view of LOFT, cue coordination in the weather environment must be accommadated. That is costly and difficult to simulate.

The effects of rain rate simulated from radar reflectivity values may eventually be needed to scale lift/drag penalties representing performance impacts due to heavy rain.

The wind shear model should be open-ended to allow for modification. This relates to the short-term versus the long-term goals. What is done in the short-term should not later be discarded; but the program should be structured in such a way that the model can be developed over time.

The next question is how do we develop the model. One suggestion is to establish a program plan. We need to clearly state the objectives and to be very specific. We need to develop the technical approach. We know in part what we want to do, but we are not necessarily sure of the next step. We have to identify resource requirements. Another issue is how we advocate this work. Do we need advocacy; or does the loose coalition of ad hoc people just meet once or twice a year? A number of programs are related to this area. The assets, if you sum them up, are fairly substantial, but management may not be aware of all the things that are going on. In other words, there is a question of applying available resources to this effort. Should we have an oversight function; and, if so, who is that to be?

After we establish how we are going to do what we want to do, the question is who will do it? We have two subsets here: 1) who is going to develop the plan; and 2) who does the work? They may be two entirely different activities. When is it needed? There are both short-term and long-term requirements. However, in any rational effort to put a plan together, the short-term work should not be throwaway, but should be consistent with the long-term goals.

MAIN AIRFRAME MANUFACTURE COMMITTEE

SUBCOMMITTEE A

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This working group addressed the large airframe manufacturers' interest in the JAWS data process. We talked about the large airframe manufacturers' needs and the development process to meet those needs. We identified the needs of the manufacturer in three areas. First is the design of equipment--the aircraft and its onboard equipment, its avionics. There are also training needs. We are required to provide data for training simulators. Finally, there is a certification need. These are three different areas, but they may end up requiring essentially the same things.

Generic models which are simple parametric models with a very limited number of parameters are needed. Also needed is some guidance as to the ranges of these parameters. We would like to see an ensemble of simple models, like a steady wind with an earth boundary layer, so that we get a gradient in the wind and an axisymmetric downburst model, which would have considerable detail in it in terms of the pressure profiles, temperature profiles, and radar reflectivity. This could be developed through a joint effort by the experimental group gathering the data in the real world and an analytic group here at Langley doing the Navier-Stokes solution. The Navier-Stokes solution would obviously have more information in it; pressures, temperatures, densities, that sort of thing, and it would be on a much finer grid, but it would have to be validated with real-world data.

To that could be added turbulence. So, you have three pieces that could be added together in some fashion and to generate a downburst of virtually any shape desired. We would need parameter ranges for things like the turbulence intensity and the delta airspeed, delta updraft/downdraft.

Toward the end of our discussion, we decided that there was both a long-range and a short-range need. People need something to work with right now, and these modeling processes we have talked about are not going to happen right now. It is going to take a minimum of a couple of years to develop the final product. In the short range, our recommendation would be to use the JAWS data as it is (5 August data), unless there is an agreement to settle on some other data, but we should

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not have too many models in circulation, and technical standards should be established for these models.

In the long run, we would hope to have the parametric models standardized so that all areas would be using the same models. This would allow reliable comparison of wind shear related studies conducted at different installations.

MAIN AIRFRAME MANUFACTURE COMMITTEE

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We spent quite a bit of time discussing proposed microburst models. For the most part, we will just reiterate the statements made by the previous committee reports. We generally agreed that math models, which capture the major characteristics of JAWS data, should be available to the user community. We feel that turbulence would be added to these models by the users. We do need, in our opinion, a best guess on a standardized model as soon as possible--a best guess by NCAR, rather than using the raw JAWS data. We feel that simulator timing and memory are not significant constraining factors in assembling that standardized model. Most digital simulators have more than enough capacity for a reasonable model. The models should be simple enough to be understandable by the user community, but they should retain realism. The fourth-dimension aspect can be covered by addition of mean wind. One user would like to accommodate potential additional needs, like frontal shears, if they are considered significantly different in terms of airplane response.

We had a brief discussion of the implementation issues, and concluded that those issues should be addressed separately from the JAWS data requirements. Any continuing activity relates to the incorporation of wind into simulations and isn't tied to microburst phenomena.

We reached no conclusion on the responsibility for definition of application of the standardized wind models for certification purposes. It was suggested that FAA should assume stronger leadership roles in the standardization of user models.

AVIONICS COMMITTEE

SUBCOMMITTEE A

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INTRODUCTION

This subcommittee emphasized the need for more information in the form of a wind shear model with statistics on important parameters. The conclusions are summarized as follows:

1. The committee requested more analysis of the JAWS data to provide information to be used in design of flight control, flight director, and wind shear warning systems.

   The further data should provide a model of a microburst with statistics in parameters such as:

   - Maximum horizontal wind differential;
   - Distance between maximum wind positions;
   - Maximum vertical wind.

   For study of systems giving early warning of wind shear, the model needs to be sufficiently broad to cover wind variations down to 1 knot/second horizontally, and 2 knots/second vertically.

2. The committee recommended that FAA require airframe manufacturers, in conjunction with avionics suppliers, to evaluate the algorithms and logic of flight director and automatic flight control systems on the present fleet of transport category aircraft.

   The evaluation is to determine the performance of these systems in microburst conditions and provide data to inform air carriers of appropriate procedures for the use of these systems in microburst wind shear encounters.

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3. The committee requested that JAWS data be provided to enable radar systems to be designed to provide early warning of wind shear conditions.

   This data should include information on reflectivity related to wind profiles, and the model described in paragraph one above.

AVIONICS COMMITTEE

SUBCOMMITTEE B

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INTRODUCTION

Some of the key points in our discussion were as follows.

1) There is a real need to provide the pilot with the type of information needed in the event he encounters a microburst. There is a lot of work going on in the warning phase, but too little attention is being given to what the pilot really needs as an aid. That's what we look for avionics to provide. In some training procedures, they are teaching that the stick shaker is a warning device. It should be noted that a stick shaker is not really a detection instrument. It was not designed as a flight "instrument". You may have everything you need programmed into it, but it was not developed or configured to be used as a shear warning device.

2) There is one certified system available flying right now, as an aid in the wind shear type of environment. The details of it are not pertinent here; but it is said that it is keyed off negative .12g buffered-type data. Avionics personnel tell us that they provide key design points based on what the customer wants. If anyone comes up with better criteria to key a device or system, they are ready to listen. One criticism of the present system was that the system is keyed from a negative .12g only and should also consider the positive side where you could receive a warning. This would then tell you that you are approaching wind shear; you're just on the opposite side of it. Again, avionics' comment was that the customer didn't want the positive criterion; but the avionics manufacturers are willing to do whatever the customer wants.

3) The next point was that progression in this field of microbursts appears to be reversed. We are designing systems and developing methods, and we really still don't understand the true mechanism of the microburst or wind shear phenomena. The large data base of the JAWS research needs study to determine what's happening.

4) A significant point which came from that discussion was that this progression style happens out of necessity. Then a wind shear incident occurs, pressure is applied by authorities like FAA to develop a system so that the airports can predict this sort of thing and close the airport. So, out of necessity, that is the way developments progress even though we would like to have time to sit back and wait to really understand the microburst situation, and then go about a logical method of solving the problems.

5) The next key point we discussed is that equipment is being developed, but it's going to be a very long time--several years, if not longer--before we have the airborne and ground equipment necessary to really understand the problem thoroughly, and introduce rules and regulations such as: a) which areas we can or cannot fly into; b) when you can or cannot close an airport; and c) when you can say pilot training is a requirement in a microburst area.

Even though we would like to have all of these things now, it looks as if the equipment required and now being developed is downstream quite a few years.

6) Another point of discussion was that there isn't enough information published yet on these phenomena, and we aren't really sure whether or not it's included in the JAWS data. Particular information, like pressure data, is needed in order to be able to analyze pressure measuring instruments and predict what happens to them when entering a microburst or wind shear. What is going to happen to all of the instruments being used to key the avionics warning devices? So, there is a real need for these types of data to help in the analysis required for avionics development.

7) The last point made is that there is a lot of work and effort going on with respect to the long-lead warning items. The radars show where you can look 20 miles downstream, or even further, to prevent entering shears. Maybe we are overlooking the fact that you need a short-term final warning device indicating to the pilot that he will encounter a wind shear in a very short time--five seconds, or so. Any short-term lead time given him will be worthwhile. Even five seconds is extremely important in order to take proper action on relatively long lead requirements, like power changes.

SIMULATOR MANUFACTURE COMMITTEE

SUBCOMMITTEE A

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INTRODUCTION

In the Simulator Manufacture session, we tried to concentrate on the main issues as they relate to simulators when used for crew training. The first issue was: Do we now have the meteorological data that we need? For microbursts, the consensus was that we do; however, there were important exceptions to this statement. In particular, there is still a need for pressure and temperature data, and getting pressure and temperature data at all the grid points is, in fact, a very, very large job. This, therefore, raises questions that the simulator manufacture session recommends be addressed by the ad hoc committee. Namely, what accuracy and resolution can we expect for parameters such as pressure and temperature? What quality of simulation can we expect based on those parameters; and will it be adequate to meet current regulations? Finally, in what time frame can this type of data be expected?

Relative to other types of phenomena, i.e., thunderstorms, squall lines, and other storm types, there is a great deal of information available. However, the problem is that this data is not processed. To process the data into usable form, again is seen as quite a large task. The simulator working session, therefore, recommends to the ad hoc committee that full weather representations, including high- as well as low-altitude phenomena, be properly simulated.

Having addressed the question of data adequacy, the next issue which was raised was how many data bases would be required to provide proper aircrew training? The concensus was that there had to be enough variability to assure that aircrews won't become too familiar with the problem that the weather situation presents to them. Also, given the visual representation of the new radar systems, the data bases should be of sufficient variety to train crews in significant features, in storms, via proper radar display interpretation. Still, the simulator working session believes that the preceding can be accommodated with a manageable number of data bases, since the variability associated with each data base provides a number of scenarios that can be accommodated for purposes of training. In this regard, as a recommendation to the ad hoc committee, we believe it would be useful if the committee could compile and propose a number of the data bases, their type descriptions, and an estimate as to when they would become available to the user community.

The next issue the working session addressed was to establish the degree of implementation (of the data bases) required for aircrew training. We have heard at this workshop that partial implementations, perhaps multi-paths through the same data base, may be sufficient.

In the context of flight crew training, the working session was in agreement that a full data base implementation which avoids canned mission types of flight is necessary for aircrew acceptance, and to meet the current FAA requirements. The working session also did not see that full data base implementation would create a computational problem, if you will, for the current data bases we are talking about.

The next question dealt with standardization of the model, i.e., whether a single weather model is achievable. Again, we have heard of the various uses for these models, ranging from flight training to avionics check-out, to research and development, at this meeting. The opinion of the working session is that a total standard model as used in flight trainers for various aircraft types will be very difficult. Within the user community of flight crew training, sufficient variability exists in the operational control and interfaces with the rest of the flight software that this may not be achievable. However, such an objective is very desirable; and, in particular, all models should be compatible with the common weather data structures. The development of a generic data set would go a long way towards making data bases and models as standard as is practical.

Another simulator specific issue that we addressed was the control of the (simulated) environment. More specifically, we questioned the compatability of current environmental control functions of simulators, if used, with this type of model and data base. Would they be proper and adequate? The opinion of the working session was that if the type of controls that we currently have on simulators are used in conjunction with advanced data bases and models, there is a very good chance/probability that the instructors can inadvertently set the controls such that the result induces negative training, i.e., create situations within the simulated environment that don't exist in the "real" world. Consequently, it is a recommendation that this aspect of simulator control of the environment be closely looked at, so that such a possibility is precluded.

The last item we covered had to do with the degree of dynamic environment simulation required for flight crew training. We heard earlier during the sessions that the amount of energy that is in the higher frequency components is not necessarily a problem as it relates to aircraft safety and aircrew performance. The observation that the simulator working session made, however, was that while the situation of high frequency components might not be important from that point of view, from a full correlation point of view, we believe it is essential that the turbulence include sufficiently high frequency content, even though the amplitudes may be small, so that proper effects can be provided by the simulator's cueing systems, i.e., motion systems, sound systems, visual systems, or instrumentation and avionics which are sensitive and provide feedback to the crew.

SIMULATOR MANUFACTURE COMMITTEE

SUBCOMMITTEE B

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MEMBERS:

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INTRODUCTION

In our session, we tried to understand what simulator manufacturers want. The best way to understand that is to understand what the users, the airlines, want. We want the simplest possible model or models consistent with reality. The problem at the moment is that the models we have, based on SRI data, can easily be overcome, resulting in the cavalier attitude by pilots towards wind shears. So, the new model must be such that it cannot easily be overcome.

We looked at the question of how many wind shears we really needed in simulation. The answer was a sufficient amount, obviously, to prevent the pilots' learning each particular wind shear so that it can be used more than once, but not so many that they would bewilder the simulator instructor. We thought, perhaps, of two on takeoff and two on landing, easily repositioned, with a selection of moderate to severe. The takeoff shears must be manageable, obviously; the landing shears should result in a go-around situation. We believe that one generic model should be able to accomplish all these aims. The model of the data should contain sufficient detail to enable a downburst to be blended into the simulator's global or steady-state winds.

We then had a discussion on turbulence. The present turbulence model is too symmetric in nature, leading to a loss of credibility of the total atmospheric simulation. In considering non-microburst cases, it is generally agreed that the current SRI profiles are unrealistic. We asked what efforts are being made to provide new and better frontal data or, in general, non-microburst data.

We considered and discussed the training viewpoint. The critical area is probably below 500 feet. There is a lot of danger that the interpolation between the 250 meter data slice and the ground data slice might result in an unreal model, particularly if we use it to derive turbulence data.

To conclude, we need a simplified model based on JAWS now. We need a commitment to provide new non-microburst data in the next few years, and we need a new improved turbulence model now.

QUESTION:

What do you mean by a simple model and what is the motivation?

RESPONSE:

What I mean by a simple model is one that is sufficiently detailed to ensure the simulator pilot cultivates a healthy respect for wind shear, but not so detailed that we get swamped with data.

QUESTION:

Another statement you made is that the wind shear has to be manageable in both the takeoff and landing. Why does it have to be manageable?

RESPONSE:

It has to be manageable in takeoff because that's what you are training for. There is not much point in training for a crash.

QUESTION:

I would argue that there is a very good point in training for a crash. That's to make people realize you can't always survive these things.

RESPONSE:

Well, I did add that we would have moderate and severe capability in our simplified models. If you feel that's a problem, we can increase the severity of this simple model as we understand what the mean and standard deviation is. We can easily wind up the gain and crash the pilot if that's what you want to demonstrate; but that's not what my airline colleagues tell me.

QUESTION:

The other point is that whan you say you need a better turbulence model, what are you referring to?

RESPONSE:

The turbulence models we use at the moment are highly symmetrical in nature. If you engage the autopilot and plot the wheel angle over a period of time and average it all out, you discover nothing much happens. The best thing you can do is just to ignore it, and you will fly through and nothing much will happen. The models are definitely symmetrical in nature.

QUESTION:

I think you will find some asymmetrical ones existing now.

RESPONSE:

I'm not sure they are available in officially published sources, are they?

QUESTION:

You say "the model" available; perhaps you refer to the Dryden model. It's not automatically equipped with that symmetric property to which you refer. It's your mechanization which causes it to be that way. There are mechanizations that can put the other features in--the patchiness, skewness, the intermittency. It's all a matter of implementation.

RESPONSE:

Yes, it was the understanding in the discussion that we had that the models we used, which we implemented, did result in the symmetric nature. People are aware of ways of getting around it; but we are not sure of those ways which are officially blessed.

QUESTION:

If you implement the Dryden model as simple linear filters that have fixed coefficients, then run random numbers through them, that does have that result, but that is not the only way to do it. You don't have to add much complexity to get the better features. There are some codes which should be published soon which show those other techniques have existed for quite a while. NASA has been working on this problem for some time, and perhaps they will document validated codes in the future.

RESPONSE:

I think we are not afraid to put in good data that is available. I think it was the feeling of the group that we have used a variety of models, but they still result in a lack of realism for users, the pilot community. Yes, we would welcome new data to try.

QUESTION:

You use the word "now" quite a few times in your recommendations. I have not heard during the course of the discussions what your desired time scale is. To produce a generic model from the JAWS data, and to do it in a serious way, is a major effort. We have every expectation of doing that, but you say that you need it now, and I would like to know what kind of time scale people are looking for. For example, what we would do is a series of individual cases, and then synthesize those cases into a generic model, along with additional data.

RESPONSE:

Some people have mentioned using standardized models, or having models issued by an authority. The problem is that various people are already using those data sets, incorrectly or otherwise. I guess "now" is as soon as is practically possible, certainly in the next few months, and if this cannot be done, then within the next few years. However, if it takes too long, everyone will have their own implementation. We will all have gone our separate ways. I think this is a golden opportunity to issue a standard model, but it can't take too long.

QUESTION:

You referred to, essentially, two classes of wind profiles--those which are survivable and those which are not. It seems to me that there is something in between that would be of some interest, that is, the ones that are survivable if you do it right; and not, if you don't. How do you draw the distinction, and where do you want to be in that spectrum from the easy ones to the hard ones?

RESPONSE:

I think that should be up to the simulator instructor. I guess the survivability could be defined as being dependent upon taking the correct actions; if you don't, it won't be survivable. With normal simulator controls, you are going to have a light, moderate, severe, percentage control, or whatever, and it is really up to the individual conducting the training how he sees fit to use it. However, if we have a generic model with a mean and standard deviation, we can then adjust the size and intensity of the profile without losing realism, hopefully.

QUESTION:

I was going to suggest that certainly as valuable as standardization of models is, a standardization of instruction is needed. An actual training procedure for this phenomenon, I think, out of development of a commonly accepted instructional procedure, will define your standardized shears.

RESPONSE:

Yes!

QUESTION:

I have an issue that hasn't really been mentioned, but is important as far as the design of standardizing the data set or a model. There has been a lot of discussion about whether or not derivatives should be used in driving the simulators. Derivatives can either be computed after the fact by using different formulas on the data or on the output of a model, or the derivatives can be intrinsically provided as part of the preliminary data analysis, or as part of the output of the model. The derivatives that you get by doing difference methods after the fact are highly filtered, and not realistic. Would you comment on what you think you need in that regard?

RESPONSE:

Well, I think we made the observation that we feel concerned that the slices are too wide, and that the whole training area is contained in one area between two slices. I feel that the resolution should be something like 100 feet or better.

QUESTION:

That's resolution. The other question is would you like the actual values of derivatives provided?

RESPONSE:

Yes, absolutely!

COMMENT: Walter Frost, FWG Associates

In terms of the turbulence models, I think one of the comments made earlier is key to my feelings about developing turbulence models; that is, that higher frequency components are needed, not necessarity from the model point of view, but from other aspects of the simulation in terms of the fuel, etc., of the aircraft, not the trajectory. That is the key, because one of the big issues is what is wind shear and what is turbulence? If you want to be strict about the entire thing, wind shear is just a large-scale, low-frequency turbulence. I think that's where the new models have to be developed. I agree that there are all kinds of turbulence models, but they are complex, and whether they add anything is not known.

COMMENT: Dick Bray

There is a need for some concerted effort and a common understanding on the question of definition and turbulence implementation. Sometimes it is very difficult to find out what the turbulence model in training simulators actually is. The only simulator with which I am familiar, at this time, is a very new one. The manufacturer-supplied turbulence model is typically extremely empirical. We have been using Dryden turbulence models for years in research and development work, and implementing those reasonably and with care. They have certainly served out purposes, and don't cause an awful lot of criticism.

SIMULATOR SYSTEMS INTEGRATION COMMITTEE

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An important point was that the pilot and the instructors needed to be more aware of recognition and flying techniques to combat wind shears, and that more time needed to be dedicated to wind shear training--something which is not currently done. We also felt the necessity of having more models besides just the JAWS to cover the whole scenario of different types of shears, like shears on takeoff, shears onlanding, different wind profiles, etc. Another recommendation was that the different wind shears had to be subjectively defined, as far as whether they were moderate, light, or severe.

We also had some recommendations regarding short-term and long-term goals. A short-term goal would be something we would need for a year or two until something very concrete was defined. We could use the August 5 data base as the base line. On a long-term basis, we would certainly require some standardized models. Some of the options might be the use of an asymmetric analytical model which would be moved around, dependent upon the instructor, a number of wind shear profiles, and a turbulence model, all of which would have to be verified by the JAWS data sets. Meanwhile, NCAR would have to provide more and better information on the current data sets for a much more universal use.

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SIMULATOR SYSTEMS INTEGRATION COMMITTEE

SUBCOMMITTEE B

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WES WILSON

We felt it was important to stress the avoidance of wind shear encounters. Give pilots the kind of information that will help them recognize the signs to look for even before they step into the airplane or while en route, and enable them to acquire all the real-time information to make that crucial go or no/go decision on approach or just prior to takeoff. As an adjunct to all this, we decided that the pilot has to get into the PIREP program with a little more vigor, and has to know that becoming part of a pilot reporting system is just as necessary for the other pilots coming behind him as the information he's acquiring from others. He must become a part of that system.

The committee felt strongly that wind shear profiles should be characterized in terms of user needs and requirements. In this regard, pilot training methodology is of key concern.

We recognized the concept of a "counter-intuitive" requirement, the pilots to do just the opposite from what standard training has taught them. We are training to two levels of instinct. We tell a pilot how to recover from a stall, and yet we tell him to pull up into the area of a stall when he's in a wind shear environment. We want pilots to be able to do both these things with equal intensity when the need requires, and we are in sort of a dilemma. We want to make sure that we can demonstrate to the pilot in the best kind of environment the airplane dynamics of a wind shear, the kind of visual and motion cues that he can expect to see and respond to, and how to interpret those instruments when they are all going in different directions. They don't mean quite the same as they do in a standard 1-g stall. So, we really have to be able to exercise with the pilot the most basic fundamental techniques to negotiate a shear. Now, I don't say negotiate as something that we want to do as pro forma everytime we fly; but it is something that he has to call out of the recesses of his mind and execute. We can't have models or simulations that are so exotic or so random that they are going to mask the very basics of what we are trying to tell him to be alert for.

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We also addressed general aviation, and concluded that this community has been largely neglected regarding the wind shear issue. We have placed priorities where the technical challenge is; modeling for simulation in this very high-technology environment really has our interest. To really address the wind shear issue in a high-visibility training environment is something that the airlines can successfully do, whereas the general aviation community cannot. We need some way to enable the private pilot to go after the kind of wind shear recognition and education that would enhance aviation safety. We talked about the FAA perhaps instituting some sort of private pilot educational program, an annual or biannual check.

In conclusion, the committee agreed that we need more focus on training and not so much on the representation of the wind shear itself. We are not out to produce the best model for the money; we're out to produce the best informed pilot that we can. We find it absolutely critical to safe operations that the pilot know what he is doing. User requirements are still very hazy. There are some airlines that have no wind shear training at all because of the negative aspect of even having wind shear in your mindset. The next level up is the airline that sends out an issue of a Boeing *Airliner* or a Douglas *Flight Approach* and says, "Here, this is what you need to know about wind shear." Some airlines, on the other hand, go very deeply into it and have much to share. What we wound up saying was that we need more airing of user needs. The committee felt that this workshop was a good start toward defining future simulator technical requirements.

GENERAL DISCUSSION

TURBULENCE MODELING

John Houbolt
NASA Langley Research Center

INTRODUCTION

I would like to mention a few points that should be kept in mind in the development of turbulence models for integration into wind shear studies. Let's consider turbulence, which is represented by a correlation function given by the simple exponential law. If we develop the spectrum that is associated with this correlation function, we get the familiar equation that you see in Figure 1, where Ω is defined as the circular frequency, ω, divided by the velocity, V. Notice in the equation there is a scale of turbulence, L, and the mean square severity value of the turbulence, $\sigma_w{}^2$. We have heard comments on to what value of severity should be used, and what value the scale should be. I would like to toss out an idea that might be very useful in simplifying this consideration, in that you can consider both the severity and the turbulence jointly as a single kind of parameter. Let's develop that notion slightly.

Take Equation (2) and rewrite it in the form shown on the bottom of Figure 1; thus, we put an L^2 in the numerator and, in turn, create a combined parameter, $\sigma_w{}^2/L$. When we examine this modified equation, we notice that at high frequencies, the scale of turbulence is completely eliminated from the problem. We should note that it is the high-frequency range which is of primary concern to airplane motion. Therefore, in rewriting the equation, we have essentially gotten rid of the scale of turbulence in describing the spectrum. We don't have to consider it anymore. You might counter, "Well, we still have the parameter, $\sigma_w{}^2/L$; we still have the problem of defining what the severity or intensity is; and we still have the problem of defining L." However, such is not the case. When you examine the mathematical modeling of turbulence, you find that you do not have to separate these two parameters. They appear automatically in combined form. Specifically, when you take turbulence data and analyze it, the value you get is the combined parameter, $\sigma_w{}^2/L$. So, you have only one parameter to think about. I have illustrated this in Figure 2.

If we have a set of turbulence data, and determine the spectra of the data, we obtain a plot of spectrum versus frequency as illustrated. If we consider the modeling equations, we can derive the equation shown at the bottom of the figure; it allows the direct evaluation of the parameter, $\sigma_w{}^2/L$. You simply enter the data at some arbitrary frequency, say Ω_1, read the spectral value at this frequency, put it into the equation, and directly evaluate $\sigma_w{}^2/L$ (this equation applies for the exponential correlation function model). You will get essentially the same result no matter where you choose to enter the spectrum, as long as you are on the straight line portion. So, indeed, the spectral data, itself, gives you this combined parameter; therefore, we have eliminated the problem of considering both severity and turbulence as two independent quantities. We have combined them into a single one. The question thus becomes, "In considering turbulence, what value should we assign to this combined parameter?

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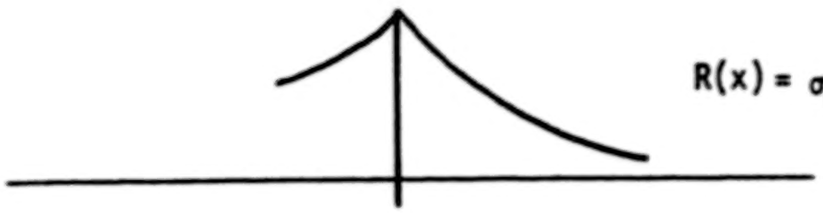
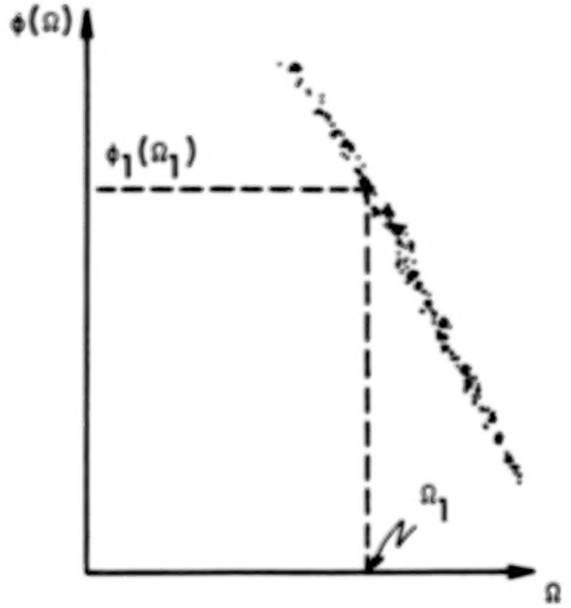


$$R(x) = \sigma_w^2 e^{-\frac{X}{L}} \tag{1}$$

$$\phi(\Omega) = \frac{2\sigma_w^2 L}{} \frac{1}{1 + \frac{\omega^2 L^2}{V^2}} \quad ; \quad \Omega = \frac{\omega}{V} \tag{2}$$

$$\phi(\Omega) = \frac{2}{\pi} \frac{\sigma_w^2}{L} \frac{L^2}{1 + \frac{\omega^2 L^2}{V^2}} \tag{3}$$

Figure 1. Simple exponential law correlation function.



$$\frac{\sigma_w^2}{L} = \frac{\pi}{2}\,\Omega_1^2\,\phi_1(\Omega_1)$$

Figure 2. Schematic of spectrum illustrating how σ_ω^2/L is evaluated.

I would like to make a few comments on this question. These are just notions, but they could perhaps be developed into a more fundamental idea. Let's consider a vertical jet, exhausting into an otherwise quiet atmosphere. If we measured the mean velocity profile, we would get the familiar bell-shaped curve that we see in Figure 3. Now, if we take a probe and go through the jet, we would get some sort of turbulence variation as indicated by this random path. On approach from the left, the turbulence becomes most pronounced as we enter the maximum shear layer. It diminishes a little as we approach the center and gets severe again at the shear zone on the other side of the jet. In other words, the maximum turbulence is generally associated at the point where there is maximum shear, or specifically, where the slope of the mean velocity profile is maximum. To first order, this slope is the velocity at the center divided by some typical jet dimension, which we will choose as the radius r. So, we can take the turbulence severity as being proportional to V/r.

We know from experiments that the scale of turbulence is connected closely to the radius of the jet; so we take scale proportional to the radius. On the basis of these two observations, we can then write the parameter σ_w^2/L for the jet as being proportional to V^2/r^3.

We might now ask how we apply this example to the wind shear type environment? My suggestion is simply this. Take the JAWS data or whatever data you have and form a smooth-moving average-type curve through the data. Don't try to put in the turbulence at the moment, but make a moving average of the data to obtain a nice smooth curve, similar to the bell-shaped curve in Figure 3. Now choose a length that is characteristic of the wavelengths--I've called it λ here--and immediately we can estimate σ_w^2/L for simulation purposes as shown in Figure 3. I suggest this as a very simple way of introducing turbulence severity and scale of turbulence in the modeling that you are considering. When we consider turbulence modeling, we should very definitely also include rolling moment in our response consideration.

Finally, besides discussing the problems of modeling, training, and simulators, we should give equal weight given to the prediction, detection, and avoidance of wind shears. It is just as important to me to be able to detect and avoid them as it is to understand and quantify them, and establish training on how to fly through them. It leads to the final point: do not fly when microbursts are present.

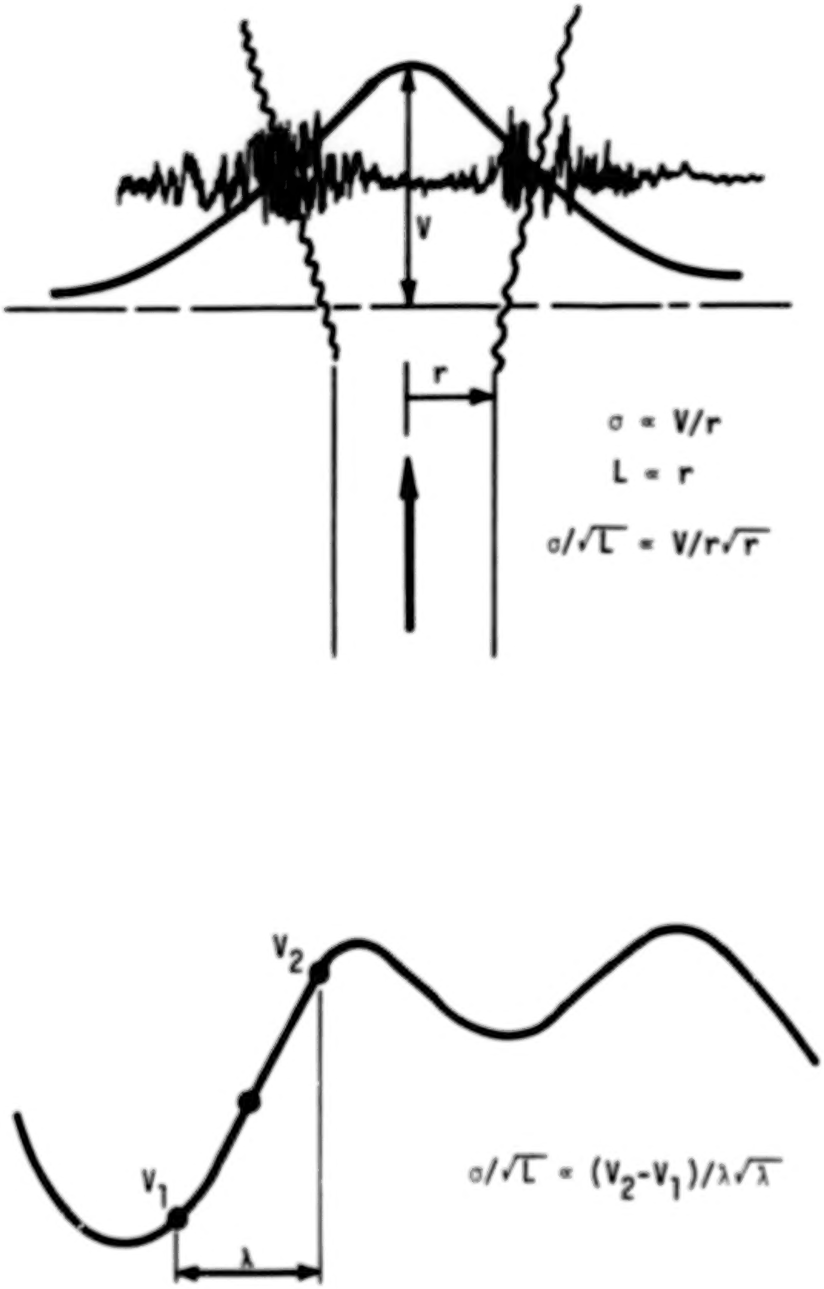

V
r
$\sigma \propto V/r$
$L \propto r$
$\sigma/\sqrt{L} \propto V/r\sqrt{r}$
V_2
V_1
λ
$\sigma/\sqrt{L} \propto (V_2-V_1)/\lambda\sqrt{\lambda}$

Figure 3.

PILOT REQUIREMENTS

William Melvin
ALPA

I think someone ought to speak to what the pilots want and need. It has been at least twelve years since we asked the industry to come up with recommended definitions of different types of wind shear as it affects the performance of the aircraft. Without response, we came up with our own terminology which is positive and negative. Since some people didn't like this terminology, it has since been discarded. In the meantime, there is no definition. This is one of the reasons why when pilots hear wind shear reports without any definitive effect it will have upon the aircraft, they are always going to add airspeed. They are going to get caught in some of the cases where they have the frontal shear conditions; they are going to add airspeed; and they are not even going to be in the same county with the airport.

One airline instituted their own procedure, which was called "Performance Increasing/Performance Decreasing". The Australians are using overshoot and undershoot, which the British absolutely will not use because they use the term overshoot, even though it's nonstandard, to mean a missed approach. That it one item.

The second is that we have, for many years, asked manufacturers to establish a level of energy that is required to properly flare the aircraft in severe performance conditions. That is, give the pilot a number that is a performance reserve he can be satisfied with so that he can flare the aircraft. This has not been done. In fact, we're still talking about flying on the stick shaker, and the stick shaker does not represent that number. We have had a major problem with how much energy does the pilot give up and still have the energy reserve to remain airborne in order to flare the aircraft and reduce the ground impact if it becomes inevitable.

I do feel I should comment on automatic systems. We feel that we like automatic systems, and we feel that in designing automatic systems for transport category aircraft the designer should consider the requirements that are placed by the military now with what they call C^3I, which means communication, command, control, and sometimes, intelligence. You are using computers to process information very rapidly to make decisions with artificial intelligence sometimes to present information very quickly to the commander, i.e., what he needs to know now. In these cases, the pilot is in a real-time control of the aircraft. Although he's talking to the aircraft systems through a computer, he is real-time connected to that computer through his control stick, and he is making those command decisions based upon these automatic systems which are bringing him that information. What we have seen in the transport world is a tendency to design the automatic system to be in total control when the pilot turns it on. He then has insufficient capability to monitor the system or even to take over the system when it fails. We are seeing some classes of accidents now where the pilots have been so dependent on the automatic system that they have gone about and done other tasks, and the automatic system has failed. It failed to enunciate that it

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because it didn't have its own proper automatic monitor and pilots have ended up 200 knots across the fence, and all of a sudden realized that the autothrottle didn't work right. So, this is what we are asking. Take into consideration what the military is really doing with automating their tactical aircraft.

INTERACTIVE DISCUSSION

QUESTION: Phil Reynolds

I would like to hear more about NCAR's ability to predict the weather conditions in which microbursts are prevalent. If this capability is at all reliable, it seems to me that we ought to have some research to get this into the system, either through the FAA or NWS.

RESPONSE: John McCarthy

There are three related components in our basic examination of these JAWS data sets. One is basic understanding and forecasting; another is LLWSAS; and another is the implications to terminal and airborne Doppler radar. It comes down to resource management, and how we get these various jobs done. We are doing an awful lot of work on the issue of forecasting, and we are trying to get these types of techniques into the NWS, so that a microburst advisory or a microburst watch can be issued for terminals where we think something is going on.

The question of oversight and how to establish technology transfer between the kinds of work we are doing and operational system has been raised. It is not a simple process. The upper management of that process in the federal government is, in my opinion, not obvious nor clear, and the reason the ad hoc committee exists is that it is a grassroots effort, at least in this domain of simulation technology, to get the thing going.

QUESTION: Dick Bray

There has been a lot of talk here about, of course, asking NCAR for a lot more data, which represents a huge amount of work. Now we have up the question of the level of effort on the prediction effort. How would you put the priority between those two efforts, or is there any need for a priority?

RESPONSE: John McCarthy

On two occasions now I have been asked to reprogram our efforts to eliminate one for the other, and my answer is we have four directions in which we need to go, simultaneously. A training program might get you through a microburst encounter, but a good microburst advisory might have done the same thing. Sure, it's a resource problem. Furthermore, we have data on gust fronts and on low-level jets. Data exist at NCAR, NSSL, and elsewhere that can be processed into your simulator problem; but it's a people/money resource, and I don't hear the priorities being established in such a way as to allow us to do those kinds of things

QUESTION: Bud Laynor

Have the resources which you think you need to accelerate this program to a satisfactory level been defined and requested?

RESPONSE: John McCarthy

Well, we have had substantial resources. I won't deny that; but the more we get into it, the more information we realize we have. The answer is that we are now into workshops like this, and into looking at some recent outputs that are helping us define what our needs are. So, the answer to your question is we think we know what they are and we are just starting to ask for the additional resources; so the answer may be yes.

COMMENT: Bud Laynor

Having a coherent program plan and resources is very important because there are a lot of people here who can lend support through various methods, including Congressional testimony and appearance support for budgets and so forth, but they have to be aware of what your resource limitations are and what support is needed.

COMMENT: Dick Schoenman

I would like to offer more aggressive approach to this than we have been discussing. I think we have a real opportunity here. First of all, the National Academy of Sciences looked into this problem and made some pretty specific recommendations. In essence, they charged the FAA with the responsibility for addressing the wind shear hazard. The FAA responded to the Chairman of the Subcommittee on Transportation, but the concensus of this workshop is that their response was not adequate. I would like to suggest that the ad hoc committee prepare a letter that represents our position as a result of this workshop. The workshop produced a lot of good information regarding low-altitude wind shear and its hazard to aviation. We should take the initiative and present our recommendation in a letter back to the FAA or other appropriate authorities. The workshop participants included a substantial number of people who have been working in this area and who represent a very good cross-section of both government and industry. Therefore, such a letter should have some impact on what's to be done in the future.

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